UNIVERSITY OF GENOA

DOCTORAL THESIS

DEVELOPMENT OF A SOFT PNEUMATIC ACTUATOR FOR MODULAR ROBOTIC MECHANISMS

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Declaration of Authorship

I, Ahmad Mahmood Tahir, declare that this thesis titled, "DEVELOPMENT OF A SOFT PNEUMATIC ACTUATOR FOR MODULAR ROBOTIC MECHANISMS" and the work presented in it are my own. I confirm that:

- This work was done wholly while in candidature for the research degree at the University of Genoa, Genoa, Italy.
- No part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution.
- Consulted published work of others is clearly attributed and referenced.
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"Life is really simple, but we insist on making it complicated"

Confucius

UNIVERSITY OF GENOA

Abstract

Department of Mechanical Engineering - DIME

Mechanics, Measurements and Robotics

DEVELOPMENT OF A SOFT PNEUMATIC ACTUATOR FOR MODULAR ROBOTIC MECHANISMS

by Ahmad Mahmood Tahir

Soft robotics is a widely and rapidly growing field of research today. Soft pneumatic actuators, as a fundamental element in soft robotics, have gained huge popularity and are being employed for the development of soft robots. During the last decade, a variety of hyper-elastic robotic systems have been realized. As the name suggests, such robots are made up of soft materials, and do not have any underlying rigid mechanical structure. These robots are actuated employing various methods like pneumatic, electroactive, jamming etc. Generally, in order to achieve a desired mechanical response to produce required actuation or manipulation, two or more materials having different stiffness are utilized to develop a soft robot. However, this method introduces complications in the fabrication process as well as in further design flexibility and modifications. The current work presents a design scheme of a soft robotic actuator adapting an easier fabrication approach, which is economical and environment friendly as well.

The purpose is the realization of a soft pneumatic actuator having functional ability to produce effective actuation, and which is further employable to develop modular and scalable mechanisms. That infers to scrutinize the profile and orientation of the internal actuation cavity and the outer shape of

the actuator. Utilization of a single material for this actuator has been considered to make this design scheme convenient. A commercial silicone rubber was selected which served for an economical process both in terms of the cost as well as its accommodating fabrication process through molding. In order to obtain the material behavior, 'Ansys Workbench 17.1®' has been used. Cubic outline for the actuator aided towards the realization of a body shape which can easily be engaged for the development of modular mechanisms employing multiple units. This outer body shape further facilitates to achieve the stability and portability of the actuator. The soft actuator has been named 'Soft Cubic Module' based on its external cubic shape. For the internal actuation cavity design, various shapes, such as spherical, elliptical and cylindrical, were examined considering their different sizes and orientations within the cubic module. These internal cavities were simulated in order to achieve single degree of freedom actuation. That means, only one face of the cube is principally required to produce effective deformation. 'Creo Perametric 3.0 M 130' has been used to design the model and to evaluate the performance of actuation cavities in terms of effective deformation and the resulting von-mises stress. Out of the simulated profiles, cylindrical cavity with desired outcomes has been further considered to design the soft actuator. 'Ansys Workbench 17.1®' environment was further used to assess the performance of cylindrical actuation cavity. Evaluation in two different simulation environments helped to validate the initially achieved results. The developed soft cubic actuator was then employed to develop different mechanisms in a single unit configuration as well as multi-unit robotic system developments.

This design scheme is considered as the first tool to investigate its capacity to perform certain given tasks in various configurations. Alongside its application as a single unit gripper and a two unit bio-mimetic crawling mechanism, this soft actuator has been employed to realize a four degree of freedom robotic mechanism. The formation of this primitive soft robotic four axis mechanism is being further considered to develop an equivalent mechanism similar to the well known Stewart platform, with advantages of compactness, simpler kinematics design, easier control, and lesser cost.

Overall, the accomplished results indicate that the design scheme of Soft Cubic Module is helpful in realizing a simple and cost-effective soft pneumatic actuator which is modular and scalable. Another favourable point of this scheme is the use of a single material with convenient fabrication and handling.

Acknowledgements

I would like thank my PhD advisor, Professor Matteo Zoppi, for supporting me with patience during the past three years. He has provided insightful guidance and leads. I am thankful to him for redundant degrees of freedom to comprehend the accomplishments during this time. I would like to express my gratitude to the Prof.ssa Rezia Molfino. Her presence in the lab was a great privilege and to have valuable suggestions and recommendations whenever required.

I am very grateful to Giovanna Naselli, for innovative ideas, insightful discussions, suggestions, and being instrumental to crank out this thesis. I am thankful to all the PMAR lab members: especially to Michal and Cuong for collaborative support in projects.

I cannot forget and I am thankful to all those who offered me a coffee; a none less than a significant ingredient to remain restive, and sometimes that was I just needed.

I would like to thank the city of *Genova*, for hosting and facilitating this journey; Yes! the journey of Ph.D. Highlighting one striking aspect of the city apart from many wonderful attractions around, "the stairs of via all'opera pia" that I swarmed up daily to reach my lab would always remind me to pursuit a stride step by step towards the crest! ...

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List of Abbreviations

SCM	**S**oft **C**ubic **M**odule
DIFERM	**D**ental **I**mplants **F**orce **E**valuation **R**Robotic **M**echanism
PDL	**P**eriodontal **L**igament
SPA	**S**oft **P**neumatic **A**ctuator
Dof	**D**egree **o**f **f**reedom
FMA	**F**lexible **M**icro **A**ctuator
HMI	**H**uma **M**achine **I**nterface
PAM	**P**neumatic **A**rtificialc **M**uscle
FEA	**F**luidic **E**lastomer **A**ctuator
EAP	**E**lectro **A**ctive **P**olymer
PDMS	**P**oly **Di** **M**ethyl **S**iloxane
EAP	**E**lectro **A**ctive **P**olymer
CT	**C**lomputed **T**omography
PKM	**P**arallel **K**inematic **M**echanism
SPS	**S**pherical **P**rismatic **S**pherical
PASCAV	**P**neumatically **A**ctuated **S**oft **C**ubical **A**acuum **V**acuum Gripper
PASCAR	**P**neumatically **A**ctuated **S**oft **C**ubical **A**rchetypal **R**obot
PASCAM	**P**neumatically **A**ctuated **S**oft **C**hewing **A**rticulation **M**echanism

List of Symbols

d	deformation	mm (millimeter)
P	pressure/stress	kPa (kilopascal)
w	weight	g (grams)
F	Force	N
T	Torque	N m
L	edge of the SCM cube	mm
D	diameter of SCM chamber	mm
h	height of SCM chamber	mm
t	thickness of top layer of SCM chamber	mm
W	Wrench - combined force-torque effect	N m
ζ	principal axis of SCM	
M	parametric configuration	

Dedicated to all in the loop…

Chapter 1

Introduction

This chapter presents the general introduction about the research idea and the relative work accomplished. It describes the need of a soft robotic actuator named as Soft Cubic Module (SCM), motivation of the work and the goals to be achieved. It introduces the method of realization to accomplish the requisite tasks. This thesis describes SCM design, its archetypal applications and consideration towards the development of advanced design. The work on SCM has been carried out as a fundamental study towards the realization of an advanced soft robotic manipulator to execute wrench cycle on the interacting surfaces.

1.1 Background and Motivation

The work towards the consideration of soft actuator development arises while addressing a fundamental design requirement for a Dental Implants Force Evaluation Robotic Mechanism (DIFERM). It seems pertinent to describe the requisition for the DIFERM briefly.

1.1.1 Dental Implants Force Evaluation Robotic Mechanism (DIFERM)

Dental implants in various forms are arranged with the help of hinges or screws into the jawbone for the replacement of teeth. These implants might not be much helpful in preserving the health of the host jawbone, at least not effective actively [1], however, they interact with the jawbone directly. In this case, the health and strength of jawbone plays very important role not only for the successful placement and long life of dental implants, but for itself as well. The selection of screw or hinge placement and its orientation becomes more critical if the jawbone is weak or damaged [2].

The strength of the bone is generally estimated either from indentation and bending stiffness of the implant after its stabilization into the bone [3], or from imaging technology [4]. Furthermore, the dentists from their experience, try to tailor the flexibility/stiffness of the prosthesis for best possible load distribution between the implant screws and the bone. There is still no way to measure or assess quantitatively the strength of the bone [5].

Upper jaw, maxilla, is uniquely placed for every individual with respect to her/his lower jaw, the mandible [6]. Furthermore, the joint of these jawbones, temporomandibular joint, varies person to person (1.2). These structural variables make the jaw movements and, hence, applied forces and moments distinctive for every person. While opting for implants, the profile of applied forces and moments may affect strength of both the implants and the jawbone.

Considering a generalized forces dissemination by the mastication movement to a natural tooth and to an implant, stem cell derived periodontal ligament (PDL) cell sheet has been arisen as a solution [8]. However, for the current practice, due to the lack of PDL that hold natural teeth inside the bone, the implants lack lateral forces and exert a larger linear vertical force.

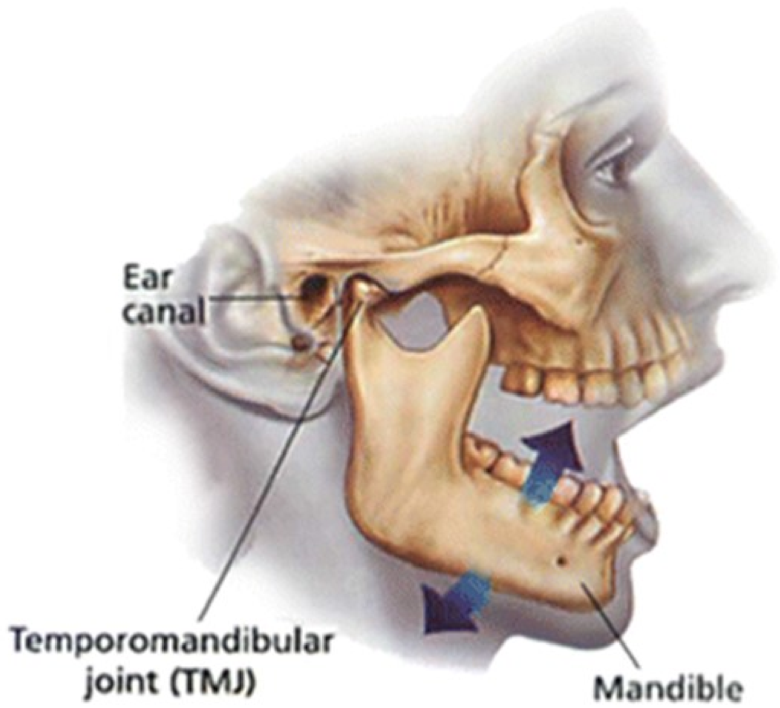

FIGURE 1.1: Human lower jawbone mandible and the temporomandibular joint [7].

In this case, an intrusive loading on adjacent teeth or implants increase the risk of bone fracture [9] (**??**). Hence, the determination of interactive loading among the dental prosthesis and the host jawbone at any specific location is critical for proper orientation and placement of the dental prosthesis.

The mechanism developed to address this requirement has a well known structure of Stewart mechanism. The use of this conventional robotic mechanism for this application is with the focus of forces execution at or around a point of interest on the end-effector with a control loop of the actuators closed in in force cycle, instead of position or velocity. The design is Applicable for the assessment of interacting forces among the two interfacing surfaces. However, this solution is based on complex kinematic design, heavy mechanical composition and is expansive in terms of overall system costs. In pursuit of finding a suitable, simpler and cost effective solution to execute forces on interfacing surfaces, the exploration leads to the development of an actuator which turns out to be diversely exploitable for realizing a range of

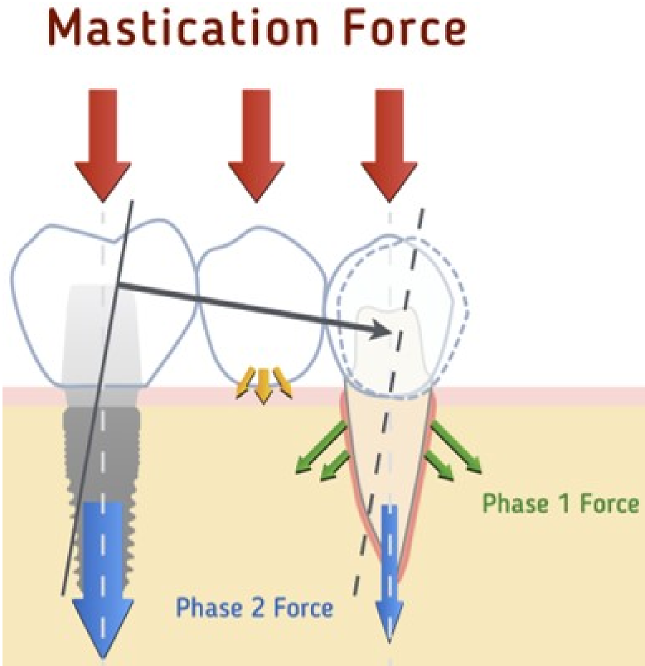

FIGURE 1.2: Later movement during mastication and loading effect of dental implant on the jawbone and adjacent teeth [10].

robotic mechanisms.

1.1.2 Inspiration Concerning Soft Robotics

Soft Pneumatic Actuators (SPAs) have gained huge popularity and are being employed in the field of soft robotics during the last decade to realize variety of hyper-elastic robotic innovations. In the developed soft robots [11], SPAs not only provide actuation means for the system, but also craft and represent a main body part of its robotic structure. Frequently, such actuators are made up of at least two parts having different stiffness characteristics. Materials with different elasticity are employed in a certain combination to limit and utilize the interacting strains in an optimized manner. This arrangement helps to achieve a desired mechanical response to produce actuation or manipulation.

The core of soft robotics technology is to implant all required components of a robotic system in the body material making it dexterous enough to concert as brain and body simultaneously [12]. Furthermore, bio-inspiration does not necessarily copycatting natural system. The intention is to imitate capabilities of biological systems, conforming to their abilities to generate actions through body deformation ensuing their inbuilt capacities and constraints [13] to produce intrinsic mechanical compliance [14].

1.1.3 The Main Motivation

The motivation of the current work is towards utilizing the promising advantages that SPAs offer, and to mediate an effort towards developing a scheme with simpler methodology yet effective and useful for realizing soft robotic mechanisms. This dissertation presents an effort aiming at the development of an SPA utilizing single material, with a single internal pneumatic actuation chamber to form an adaptable multipurpose actuator with a simple construction. The module is cost effective both in terms of its developmental process and disposal of the impaired or damaged components. The aim is to develop a pneumatically operated soft actuator, named as SCM to realize modular soft robots including grippers, bio-mimetic and multi Degree of freedom (Dof) mechanisms (1.3).

1.2 Rationale and the Contribution

A soft actuator is to be realized with the above mentioned objective keeping in view some basic considerations: the design should be simple, the fabrication should be convenient, and with the capacity to be employable for the development of soft robotic mechanisms in a cost effective manner.

The objective of this thesis is to explore an effective design to realize a soft actuator. Various configurations have been examined and developed to achieve the following objectives:

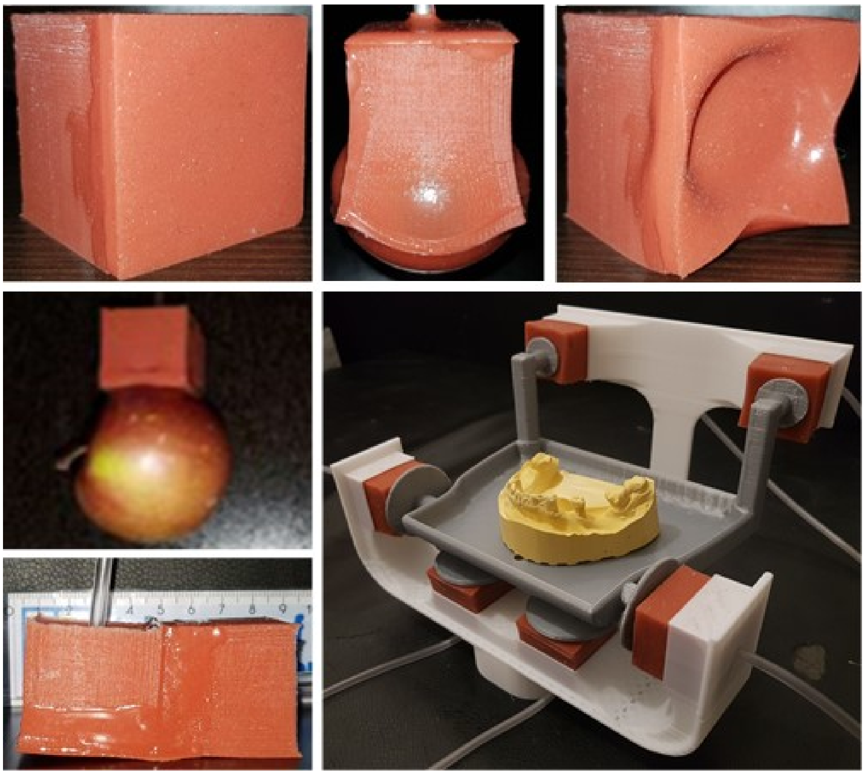

FIGURE 1.3: SCM and respective developed applications.

(a) Realization of a suitable SCM design: Designing a system capable of generating deformation and exhibit relevant force on the interfacing or interacting surface for required actuation.

(b) Modularity and scalibility: Realizing an architecture that can facilitate for best possible utilization of the developed SCM in various combinations and sizes for a range of different applications.

To achieve the design and thesis objectives, SCM has been finalized based on its applicability and flexible design scheme. The proposed soft robotic actuator SCM is a silicone rubber material based modular design with internal fluidic chambers that can generate forces mainly in single Dof. This design has been validated as a soft vacuum gripper [15]. Furthermore, thanks to the external cubical shape of the SCM, several cubes can be arranged to configure multi-unit soft systems. An elementary assembly of two modules, which is able to perform locomotion on a flat ground, has been developed as well. It is further aimed at evaluating and validating the design for the development of more efficient and effective modular soft robots employing the developed scheme.

1.3 Thesis Outline

- Chapter 1: This chapter provides the overview and presents the general introduction about the research idea, its emerging background, the motivation to carry out the efforts in the specified direction, and the relative accomplishments. It briefly reviews the relevant literature and describes the rationale for the developed soft actuator.

- Chapter 2: It presents the background information and detailed literature review on the state of the art related to the developments of SPAs. It also prescribe the line of action and methodology being followed for the development of SCM and consequent applications.

- Chapter 3: This chapter is the description of the architecture and design of the SCM. It highlights the material characteristics, design analysis, and fabrication procedure for the SCM. It introduces the developed SCM module as well.

- Chapter 4: The developed SCM has been employed for its validation. Chapter 4 is reserved to enumerate application of SCM as a gripper. One SCM module has been employed for this application to describe and analyze the gripping capability of the soft gripper named as PASCAV.

- Chapter 5: The developed SCM has been further employed to evaluate its capacity in multiunit combination. Chapter 5 provides the details about the application of SCM as a bio-mimicking crawling mechanism.

two SCM modules have been employed for this application to describe and analyze the mechanism named as PASCAR.

- Chapter 6: This chapter presents a mechanism under consideration based on SCM leading towards the future work direction.This SCM based configuration of a multi-Dof Mechanism, aiming at replicating human chewing movements. It presents the potential design of the soft chewing mechanism, PASCAM, comparative to a system employing conventional Stewart parallel mechanism.

- Chapter 7: It briefly discusses and evaluates the contributions and analyze the overall capacity of developed SCM and consequent configured models. It will be discussing the suitability of the effort for realizing soft robotic mechanisms. It concludes by indicating the shortcomings, future directions and requirements for proceedings.

Chapter 2

State-of-the-Art: a Literature Review on Soft Actuator

2.1 A Brief Note on History of Soft Robotics

The recent state-of-the-art of bio-inspired soft robotics has been revolutionized from a state which was presented by way of fiction just a few decades ago. Although they are still abstract, now they are being transformed from fictional to factual entities. The development of robotic actuators employing soft materials initiated in late 1980's. Toshiba Corporation's flexible actuator can be considered as the foremost development in the field of soft robotics as shown in Fig. 2.1.

Toshiba realized a flexible micro-actuator (FMA) for maneuvering micromanipulators and robotic mechanisms in 1989 [16, 17, 18, 19]. Made of fiber-reinforced rubber, the FMA was a three Dof actuator capable of producing miniaturized movements pretending fingers, hand, arm and leg actuation. Three Dof were designed through three channels which were actuated by electro-pneumatic or electro-hydraulic pressure thus causing axial stretch or bending effect [20, 21]. Series of connected FMAs can produce increased Dof for various applications as shown in Fig. 2.2 [22, 23]. Later on in late 90's, based on nature of application, material and FMA actuation characteristics;

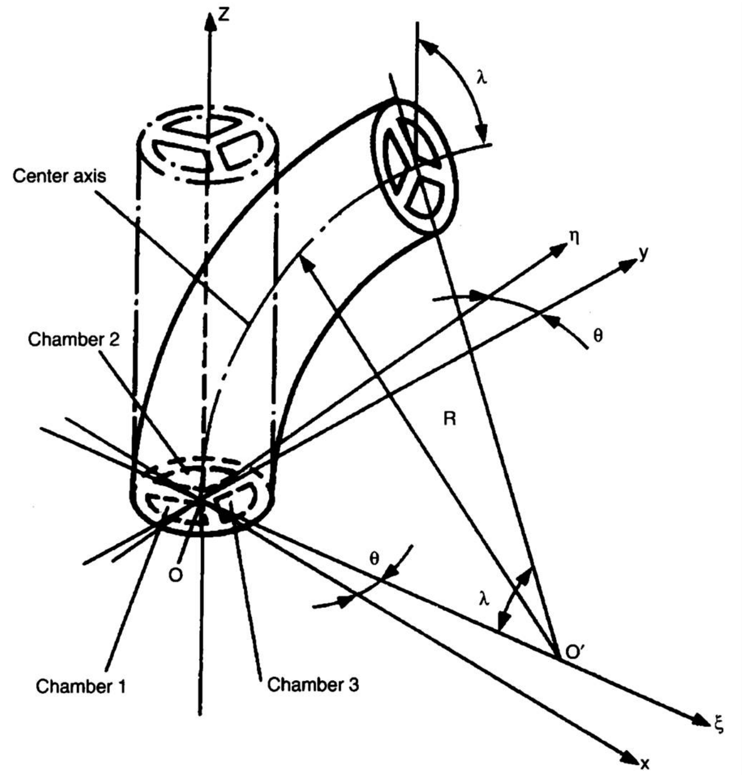

FIGURE 2.1: Three Channel FMA Structure [20].

different fabrication techniques like molding [24], extrusion molding [25], and stereo lithography [26] were implemented to craft compliant FMAs [27].

While demonstrating FMA as the foremost soft robotics innovation, it is appropriate to recall, in the context of soft robotics, the invention of artificial muscle for prosthetics introduced as McKibben Muscle in 1957. Although some other fluidic actuators are even older, McKibben Muscle can be considered as the prominent invention in robotics. It was implemented in 1957-58 to actuate hands and fingers of polio affected Karen McKibben, the daughter of Dr. Joseph Laws McKibben [28, 29]. The innovative design, by German scientists, incorporated bellows cylinder inflated by carbon dioxide, thus acting as a muscle generated pinching movement of attached paralyzed fingers (Fig. 2.3).

Therefore, it is perceptible that the ground breaking work for soft robotics was accomplished in late 1980's in the form of FMA development in collaboration of Toshiba Corporation and Yokohama National University Japan.

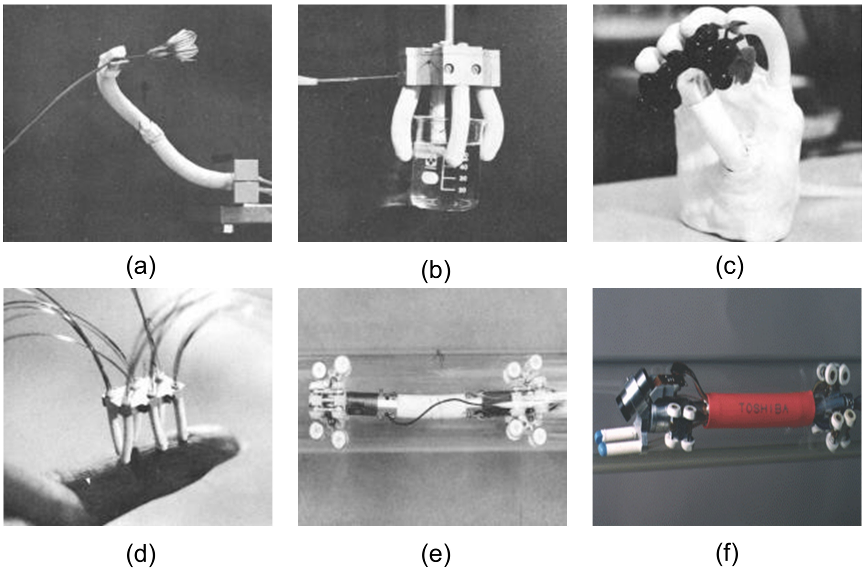

FIGURE 2.2: Arm, finger, hand, legged, mobile (pipeline inspection) robots based on FMA [23, 24].

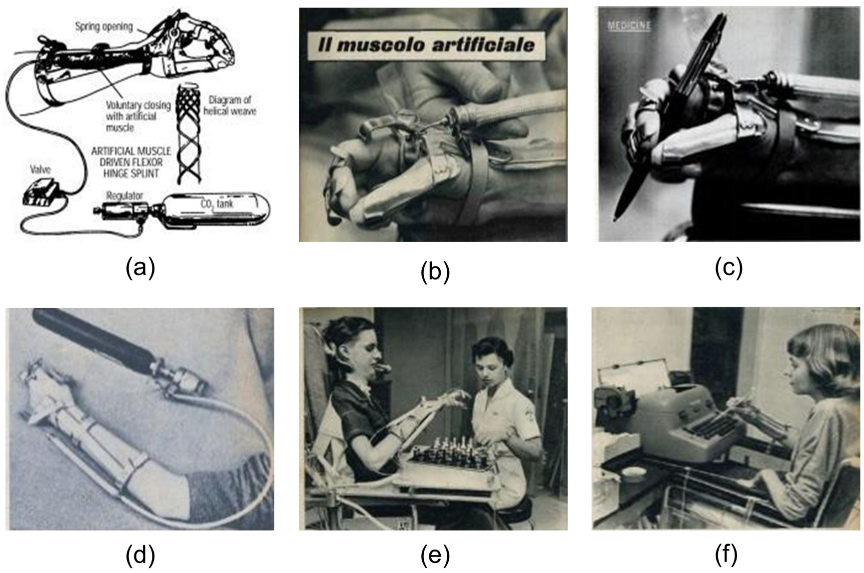

FIGURE 2.3: McKibben Muscle Design and applications [29].

During 1990's, major work was accomplished on the development of soft grippers [30] like human finger tips, and on the soft skin development which was utilized both as skin and for touch sensing to improve the human-robot interaction [31, 32]. It is also worthy to mention that efforts were made to introduce soft joints making it possible for robotic structures to be more compliant and safer especially while interacting with humans [33]. Most of those primary undertakings were originated in Japan, USA and UK.

2.2 Outfit of a Soft Robot

A soft robotic system generally consists of same elements like a conventional robot including body structure, actuation mechanism, sensors and transducers architecture, electronic and control interface, and power sources [12]. Some of the soft robotic systems may include Human Machine Interface (HMI) as well. It is necessary to distinguish between soft bodied robots and hard bodied robots with soft-like actuation. Both categories may have impersonation of bio-inspiration and may represent flexible and compliant actuation, however, the objective of soft robots is to embody all elements of a robotic system into soft material avoiding rigid links and mechanisms. This ambition indeed set apart soft bodied robots, composed of soft materials of various grades, as soft-robots [12, 34]. More specifically, both of these categories may have similar morphology, but they will be differentiated substantially based on materials they are built from. The soft robots are usually fabricated from elastomeric materials which are organic in nature [35]. The advantage of relying on soft materials for body construction of soft robots is the variability of conceivable motions that such materials can offer with a simple structural mechanism [35, 36]. Soft actuators which have been employed and are being investigated for soft robots are mainly of four types namely tendons, Pneumatic Artificial Muscles (PAMs), Fluidic Elastomer Actuators

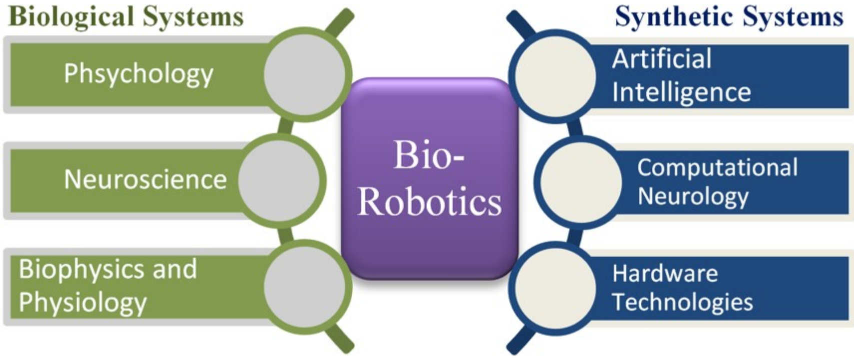

FIGURE 2.4: Bio-robotic correspondence to Biological and Synthetic Systems [14].

(FEAs), and Electroactive Polymers (EAPs) [12, 35]. Actuators are generally organized to generate bidirectional motion which offers an added advantage of better compliance. Conventional sensors and electronics are still in use though recently researches have been started to investigate and modernize soft, flexible, stretchable and bendable sensors.

The core of soft robotics technology is to implant all required components of a robotic system in the body material making it dexterous enough to concert as both brain and body simultaneously. Furthermore, bio-inspiration does not necessarily intend copycat the natural system. The intention is to imitate capabilities of biological systems, conforming to their abilities to generate actions through body deformation ensuing their in-built capacities and Constraints [13] to produce intrinsic mechanical compliance (Fig. 2.4).

What do we need in a soft robot generally – a flexible body composed of soft material like polymers capable of producing continuum movements; soft actuators like tendons, PAMs or FEAs; sensors and driving electronics which are still conventional mostly; control techniques and power source – the specific components obviously depend upon a specific design and application of a robotic system. Together with material selection, it is indispensable to configure the shape and locomotion of the system. In soft robotics, it is crucial to address material selection, profile design and fabrication, and design of locomotion scheme in parallel to effectively utilize material properties to implement a conforming locomotion gait [37].

2.3 Soft Pneumatic Actuators (SPA)

SPAs have gained huge popularity and are being employed in the field of soft robotics during the last decade to realize variety of hyper-elastic robotic innovations. In the developed soft robots [11], SPAs not only provide actuation means for the system, but also craft and represent a main body part of its robotic structure. Frequently, such actuators are made of at least two parts having different stiffness characteristics: materials with different elasticity are employed in a certain combination to limit and utilize the interacting strains in an optimized manner in order to achieve a desired mechanical response to produce actuation or manipulation. One of the most famous SPA is described in [35]. This actuator is made of two parts: a pneumatic chamber composed of EcoFlex 00-30 and a layer of polydimethylsiloxane (PDMS). The latter is stiffer than the former and provides longitudinal inextensibility to one of the faces of the actuator. As a result, the actuator performs planar bending and can be used as a finger to grasp an object or as a leg for a crawling robot [38]. Based on this principle, soft hands and orthoses (e.g., [39, 40]) have been developed; other examples of SPAs with relatively inextensible layers can be found in [41, 42]. In some works, rather than using such layers (or, in some cases, in addition to them), the strain of part of the elastomeric matrix is limited by recurring to fibers: in [39, 43], sewing thread is wound along a double helix on the soft body of the SPA to avoid ballooning effect. In [44], the fiber plays a major role: it is wound on the external surface following a helicoidal path, whose angle determines the mechanical behavior of the actuator; how the authors demonstrate, SPAs having different fiber angles can be properly combined in series, to build a soft snake able to move through a pipeline. In another work [45], the SPA consists of a soft cylindrical component made of EcoFlex 00-30, with three longitudinal channels. In order to reduce the ballooning effect, an accordion-like structure is embedded in the body of the actuator. Such structure is made of a silicone rubber whose hardness is higher than the one of EcoFlex 00-30 and therefore provides additional stiffness. So far, the combination of several materials to build SPAs has turn out to be a winning choice; however, it introduces complications in the fabrication process. Another convenient approach is the development of blocks or units to build modular soft robots: in [46], inflatable and non-inflatable units are provided with screw thread connectors to allow easy assembling and disassembling of soft mechanisms. The units described are made of several materials. SPAs have been recognized as one of the basic building block in the field of soft robotics in the last decades. Electro-pneumatic or electro-hydraulic elastomeric actuators were initially employed in 1980's to realize biomimetic mechanisms [16, 18, 19, 46]. PAMs or McKibben muscles were also used to develop soft prosthetic and rehabilitation systems [17, 47, 48, 49, 50, 51, 52]. Some latest designs for the bio-inspired soft mechanisms have been reported in [53, 54, 55, 56, 57]. SPAs facilitate actuation as well as serve as a part or body of the main actuator or the soft robotic structure [57].

2.4 Concept of the Current Modular Soft Actuator

In the work presented in this thesis, a modular approach has been adapted, however the aim is at developing an SPA made up of only one material. This scheme introduces SCM having a single internal chamber, and its deformation under pneumatic actuation has been utilized. Design validation of this pneumatically operated soft actuator SCM, to realize modular soft robots like grippers, bio-mimetic and multi Dof mechanisms, is under consideration. The SCM has already been employed as a single unit soft vacuum gripper

PASCAV [15], and a two-unit PASCAR crawling mechanism. A multi-Dof mechanism PSCAM is also under consideration.

Chapter 3

Soft Cubic Module (SCM): Design and Analysis

3.1 Geometrical Design and Internal Actuation Chamber

SCM is the fundamental building block of this design scheme with an internal pneumatic actuation chamber. As the name suggests, SCM has a cubic shape while its actuation chamber or cavity resides under one of the surfaces of the cube, which is the actuating face of SCM. To design the internal actuation cavity, different shapes have been considered and analyzed at various orientations inside the silicone cube in order to achieve an effective deformation and respective resultant forces. The produced deformation can be utilized further to achieve the required actuation of a particular SCM which may be employed as a soft system in standalone configuration, or in combination of two or more SCM blocks. Spherical, elliptical and cylindrical profiles of the internal actuation cavity (Fig. 3.1), with varied positions and orientations have been simulated for static hyper-elastic behavior of the actuated SCM in 'Creo Perametric 3.0 M 130' to validate their respective performance in terms of effective deformation and the resulting von-mises stress. Although the SCM module has proven scalability characteristics, let's consider a 3030mm

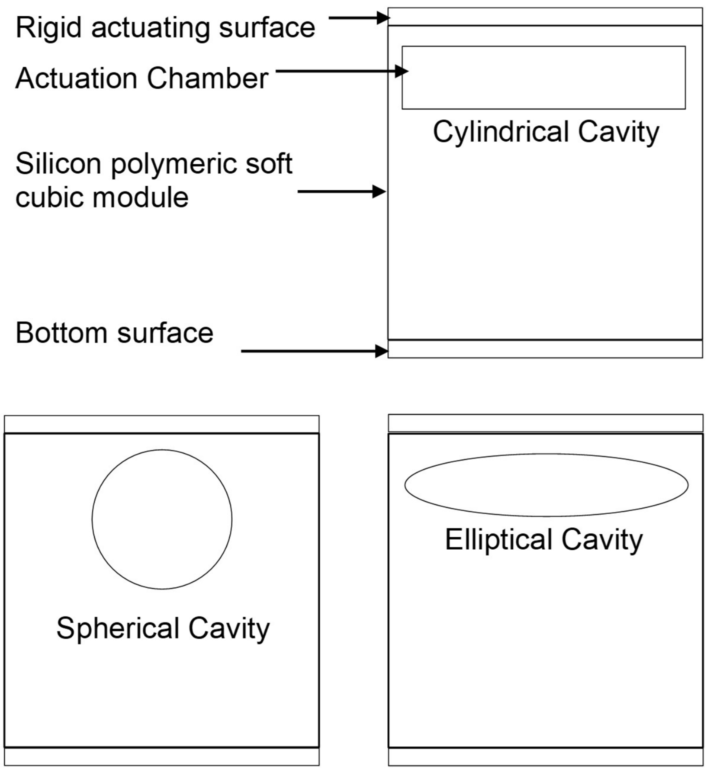

FIGURE 3.1: SCM with cylindrical, spherical and elliptical actuation chambers: For load testing, SCM subjected to fully constrained bottom plate whereas a rigid plate simply attached to top surface of SCM.

cube for the purpose of demonstration and analysis. The spherical chamber with 12mm diameter is touching the center of the cube under the actuating face with minimum 2mm surface thickness. The elliptical chamber, with major and minor diameters of with 24mm and 12mm respectively, is oriented between the faces of the SCM orthogonal to the actuating surface at 45 to the z-axis. The cylindrical chamber is positioned under the actuating face with minimum 2mm surface thickness around and at the top of the chamber.

Increasing trends of output load set and the output stress and produced deformation against applied pneumatic pressure have been observed. Selected set of results for 1kPa to 3kPa applied pressure have been presented in Fig. 3.2 and Fig. 3.3. It is evident form the results that increasing the effective actuated area, against the selected surface being actuated, increases the output stress and the deformation. This scenario is best possible to achieve

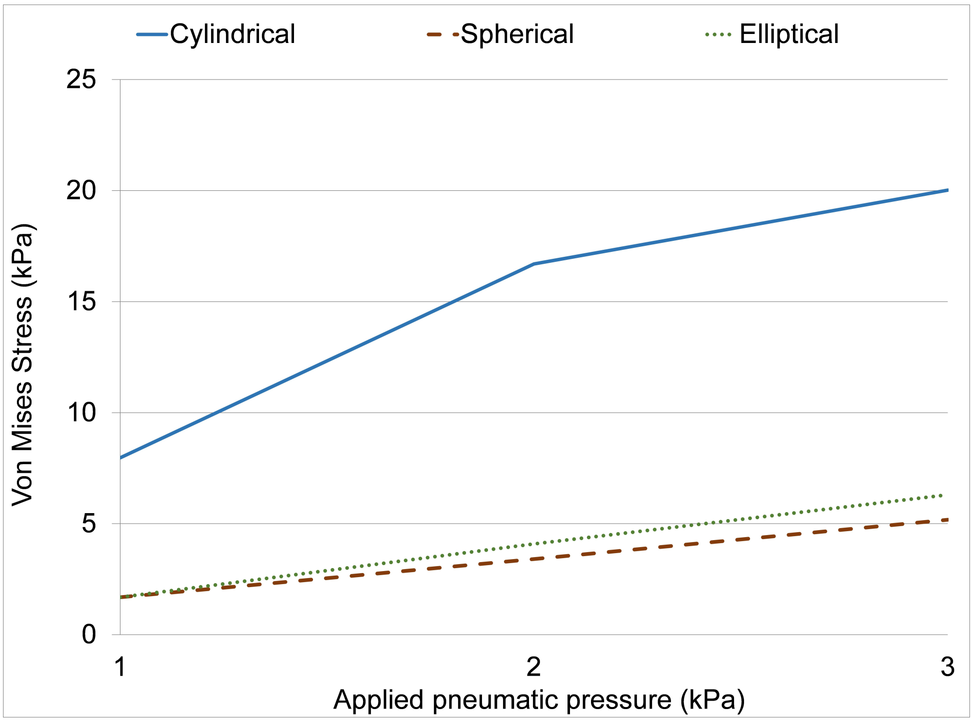

FIGURE 3.2: Selection of actuation chamber shape: Von Mises Stress (kPa) against applied load set. Resultant stress against 1kPa to 3kPa applied pressure to the actuation chambers.

employing cylindrical profile of the actuation chamber, as in case of spherical and elliptical shapes, either the produced stress is absorbed by the material itself or the large deformations against higher pressures make the cube unstable due to the resultant stress and deformation against all surfaces of the cube.

3.2 Actuation Chamber Design and Analysis

SCM design has been considered to make it a standalone stable unit, which can further be integrated in multiple unit configurations. Furthermore, to generate actuation, SCM needs to be capable of generating effective deformation at least on one surface of the cube. This deformation, like along z-axis orthogonal to the actuating surface, should be sufficient enough to exert forces on the interacting surface, whether it is some external body or another integrated SCM unit. Based on the considered profiles and orientations of the

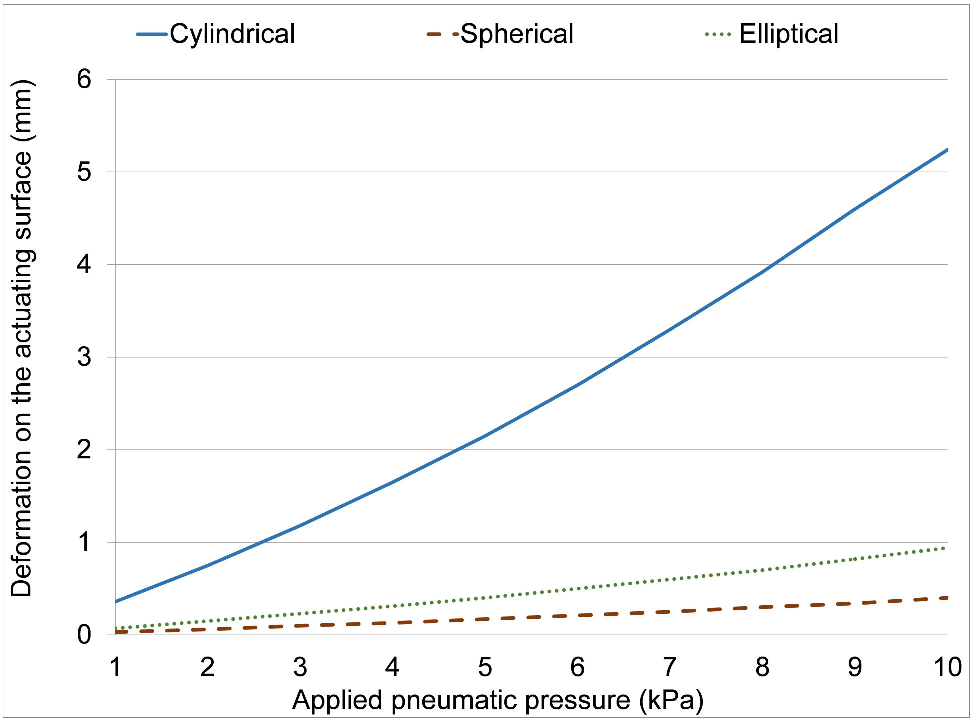

FIGURE 3.3: Selection of actuation chamber shape: output deformation (mm) against applied load set. Deformation at the actuating surface against applied pressure from 1kPa to 3kPa.

internal actuation chambers of SCM, the output load set and produced deformation suggest that the chamber should have maximum interacting surface area to the corresponding actuating face of the SCM in order to achieve the requisite results. Furthermore, since the SCM is composed of a hyper-elastic material, circular and elliptical shapes will have more soft material around the actuated chamber absorbing the pressurization effects which reduces promulgation of effective deformation and output loads at the required face of the SCM. These constraints suggest that the actuation cavity needs to be in the proximity of the target face of the SCM as well as should have maximum possible surface area or space to impart maximum deformation and forces. As already stated, another aspect to optimize the size and placement of the actuation chamber is stability of the SCM unit. Spherical and elliptical shapes with various dimensions and orientations, eventually affect all the faces of the cube. This would be resulting towards the instability of the cube as well

TABLE 3.1: Dimensions of the SCM

Symb.	Description	Value
L	edge of the cube	30mm
D	diameter of the chamber	$26\sim 27mm$
h	height of the chamber	6mm
t	thickness of the top layer	$2\sim 3mm$

as make it difficult to utilize SCM in a modular multi-unit configuration effectively. Whereas the cylindrical chamber deforms the nearest surface of the cube in such a way that the opposite face remains at normal state providing at least one surface for stability. This behavior is helpful in utilizing the SCM in majority of its multi-unit configurations. In this purview, the cylindrical actuation camber as shown in the Fig. 3.4 has found to be the most appropriate profile satisfying design and required output performance for the development of SCM. Cylindrical profile design is further discussed here in detail.

3.3 SCM: the Soft Actuator

3.3.1 Cylindrical Actuation Chamber Configuration

Cylindrical actuation cavity is considered and validated based on simulations analysis and the developed silicone polymer modules. The flat surface of this cylindrical actuation chamber is oriented parallel to a face of the SCM underneath the 2mm thickness of outer surface. The central axis of the cylindrical chamber is coincident with Z-axis which is one of the principal axes of the cube; from now, this axis will be denoted as axis ζ. This orientation of the actuation cavity has been found to be the most appropriate against applied pneumatic pressure. Outline of the side view of the SCM is shown in Fig. 3.4. The dimensions are reported in Tab. 3.1.

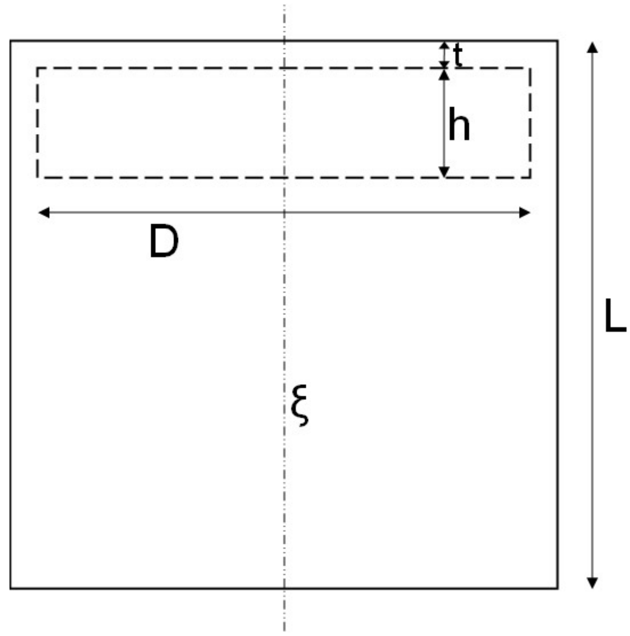

FIGURE 3.4: Side view of the SCM. The soft actuator with its internal actuation chamber in cylindrical shape which is visible in dashed lines.

3.3.2 Material

SILICON MIX® provided by ITALGESSI Srl is a vulcanizable silicone rubber at room temperature with high fluidity. The two components of the mix are silicon (A) and catalyst (B). For the current experimentation and profiling of actuation behavior, we have used a red-colored silicone having Shore A hardness 4. An optimized mix ratio of the two parts has been accustomed after a series of testing and analysis to achieve softness with least stickiness of the rubber. The current modules have been developed with 80/20% (4:1) ratio of components A and B. Each module takes 2 to 3 hours for curing at room temperature. The weight of the module is 45 g.

The material has been subject to tensile test to obtain its stress-strain relationship. We have imported such results in Ansys Workbench 17.1® environment, in order to derive a model for the material behaviour. The best fit has been obtained with the Arruda-Boyce model, with initial shear modulus $\mu = 12.37$kPa, limiting network stretch $\lambda_L = 1.602$ and incompressibility parameter $D1 = 0$.

FIGURE 3.5: Molds and respective molded parts to build the SCM. 3D printed molds and the molded silicone.

3.3.3 Fabrication of SCM

We fabricate the SCM in two parts: the main body, which includes the pneumatic chamber, and a square layer to cover the chamber. Therefore, we have built two molds, recurring to 3D printing using PLA thermoplastic: the main mold is 30×30×27mm with pneumatic chamber disk cell; the second is 30×30×3mm. The molds are shown in Fig. 3.5, together with the molded rubber parts obtained.

The two molded parts are then glued together using the same silicone mix with same mixing proportions. The fabricated SCM is shown Fig. 3.6

3.4 SCM Actuation Characteristics

As one can expect intuitively, the deformation of an independent actuated SCM involves mainly the top face and secondarily the side faces. The deformation of a single actuated SCM, with cylindrical actuation chamber as described, exhibits the deformation of the chamber's corresponding face and secondarily the edges of side faces Fig. 3.7.

FIGURE 3.6: SCM model.

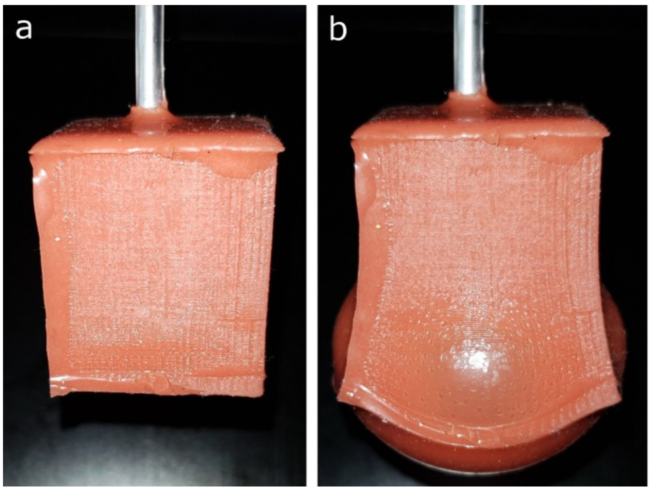

FIGURE 3.7: SCM actuation. Normal (a) and actuated configuration (b).

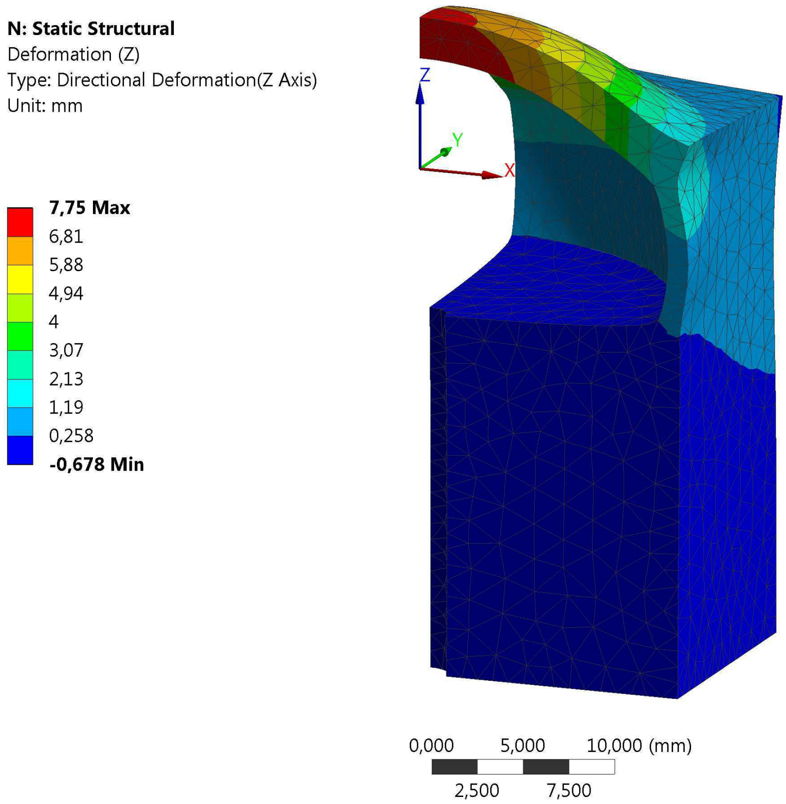

FIGURE 3.8: Directional deformation (d_t) along ζ, coincident with Z axis in the system of reference of the simulation environment. The internal applied pressure is 3 kPa. Only a quarter of the SCM is shown.

The point undergoing the maximum displacement is the center of the top face; such displacement occurs along axis ζ and we denote it by d_t. At each of the four side faces, the deformation involves a smaller region, whose size is related to the height of the internal chamber; on this face, the maximum displacement (d_s) occurs along the direction orthogonal to ζ and to the face. This is due to the fact that the minimum wall thickness of the SCM is found at half of the edge length. Such thickness is the same at all the four sides of the cube; there are, in fact, two symmetry planes. Such symmetries have been taken into account when performing finite element analysis on the SCM; the points undergoing the displacements d_t and d_s are visible in Fig. 3.8 and 3.9, respectively.

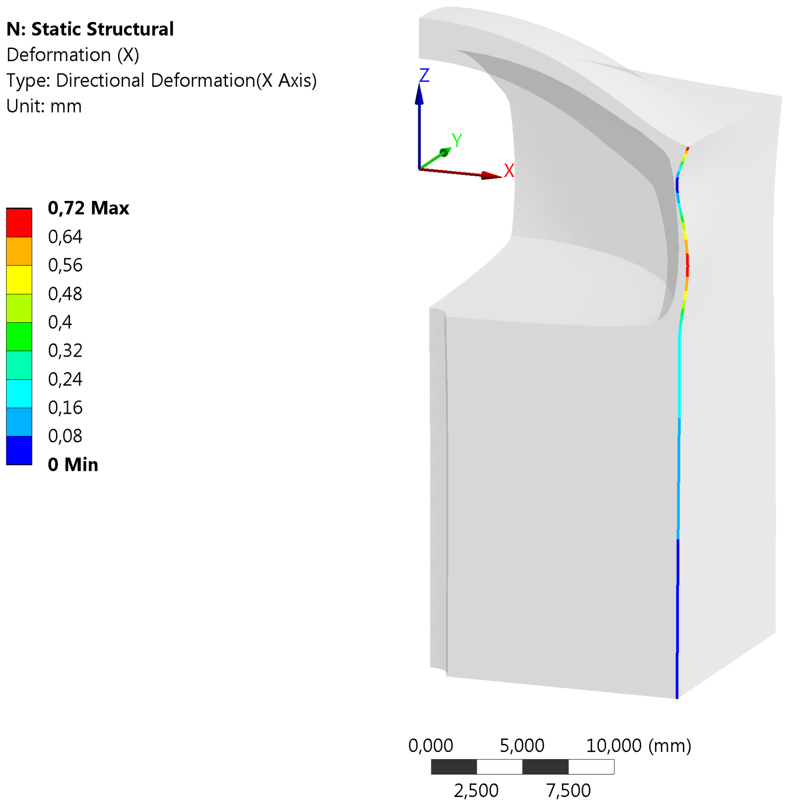

FIGURE 3.9: Directional deformation (d_s) along X axis in the system of reference of the simulation environment. The internal applied pressure is 3 kPa. Only a quarter of the SCM is shown.

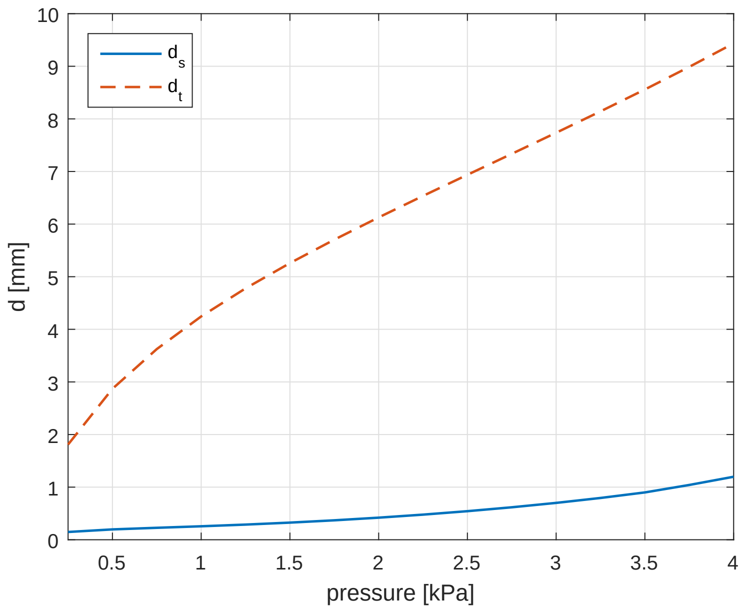

FIGURE 3.10: Displacements d_s (full blue line) and d_t (dashed red line) vs. internal pressure inside the chamber of the SCM.

Due to the symmetry conditions, the computation is performed on a quarter of the SCM. The mesh is entirely tetrahedral; the load applied is a uniform pressure equal to 3 kPa; as a constraint condition, the bottom face of the SCM (which stores no strain energy, being far from the actuated zone) is fully constrained. All the simulations that we have performed on the SCM take into account both material nonlinearities and the effect of large displacements.

By means of the finite element simulations, we have observed that the ratio

$$r = \frac{d_t}{d_s} \tag{3.1}$$

depends on the value of the applied pressure. Both d_t and d_s increase when pressure increases (see Fig. 3.10); however, their ratio is not constant and presents its maximum between 1kPa and 1.25kPa, as reported in Fig. 3.11. This means that increasing the pressure over 1.25kPa results in an augmented relevance of the deformation at the sides of the module, although the main displacement is provided along ζ at any pressure value.

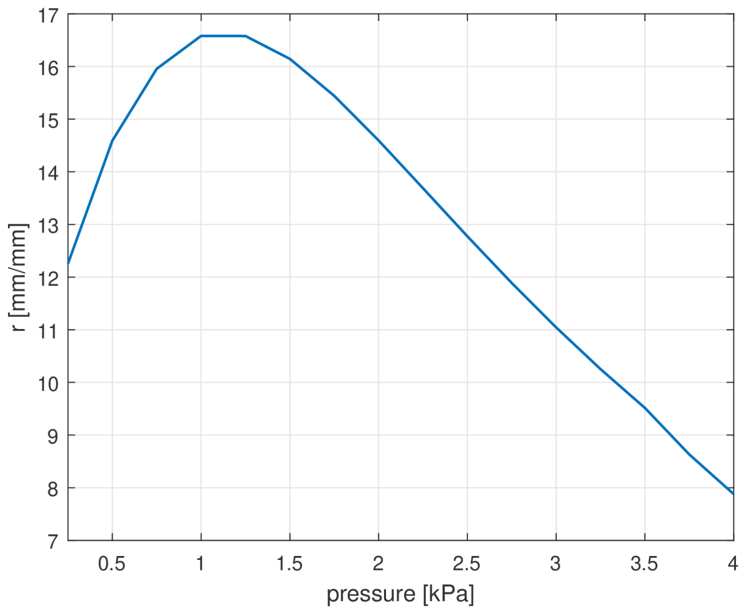

FIGURE 3.11: Relationship between directional deformations d_t and d_s

3.5 SCM Design Evaluation and Results

This current effort is a primitive presentation of a targeted work to realize a scheme which will completely be based on design optimization. The aim is to make this scheme modular and economical. The initial results accomplished by the SCM are running the notion: cubic shape makes it easy to be modular in any orientation; single circular inner actuation chamber is easy to mold and to connect to the pneumatic line; pneumatic actuation is simple and safe; the material is convenient for molding and capable of soft actuation. A supplemental advantage of this design is the use of single material for the SCMs, which is easy to handle to use as well as to discard avoiding hefty contamination to the environment; this latter problem has been raised also by other authors (see e.g., [58]). As previously explained, the molding process and maintenance of the SCM are convenient as well. Simply the two- part mix silicone can be poured into mold and leave for curing, without adding additional layers of fabric, fibers, or any other content. The same mix is useful for joining parts of the SCMs, modifying assemblies, and repairing fractured or punctured blocks. With proper repairing, the blocks have the same strength of actuation and output stress bearing capacity. Another advantage, with essential care, is that the joined SCMs can certainly be fragmented into basic molded shape and then can be reused again for new system development. This re-usability makes this approach cost- effective and environment friendly. The current SCM design is using only one surface for effective actuation while the remaining block is thick flexible rubber. This structure is useful for stability of the SCM individually as well as in combination with others, by maintaining firm contact with ground surface. This configuration is potentially useful to design multi Dof robotic systems and manipulators. To name few of them, single SCM block soft pneumatic gripper, bio-mimetic crawling mechanism utilizing two SCM blocks, 6-Dof manipulator and soft pneumatic wheel employing more than two units of the SCM. Some of these impending systems have been developed and are being evaluated while others are under consideration for development in the upcoming phase of this work.The fabricated SCM modules show linear behavior against actuating pressures both in vacuum gripper configuration PASCAV: a Pneumatically Actuated Soft Cubic Archetypal Vacuum gripper [15], as well as two block bio-mimetic crawling mechanism PASCAR: a Pneumatically Actuated Soft Cubic Archetypal Robot which is under development. A static structural analysis of PASCAR, consisting of four steps, in which the actuation pressure in two SCMs is modeled. A multi-Dof mechanism PASCAM - the Pneumatically Actuated Soft Chewing Articulation Mechanism is under further discussion and development. All these systems are further described in the consequent chapters.

Chapter 4

PASCAV Gripper: a Pneumatically Actuated Soft Cubical Vacuum Gripper

4.1 Introduction to Soft Gripper and the PASCAV Gripper

Soft gripping mechanisms prospectively offer many advantages over traditional structures in terms of compliance and the adaptability towards the interacting environment [34, 35, 59]. Such grippers in different shapes and designs have been realized for a variety of applications in recent years.

A variety of design schemes have been adapted to develop soft grippers. Grippers with actuating fingers for handling of objects with varying shapes, sizes and stiffness have been reported in [12, 24, 54, 60, 61, 62, 63, 64]. Some grippers have been developed in combination of soft and rigid parts arrangement [56, 65, 66, 67], exploiting flexibility and compliance of soft materials. These designs are based on working principle to utilize the already known and well established behavioral properties of metallic fragments. Another approach to design gripping mechanisms is to use the granular jamming effect of granulated material filled inside some flexible membrane [68, 69].

Bioinspired approaches mimicking the underlying actuation principles of natural organisms to develop gripping mechanisms have become a common practice. Following this approach, a single arm-shaped grasping structures inspired by octopus arm have been realized employing different techniques and materials [70, 71, 72]. In a similar effort, Festo developed a chameleon tongue inspired gripper employing a double acting cylinder fitted with silicone moulding [73].

In another effort, elephant trunk imitation was incorporated to manipulate heavy loads [74, 75, 76, 77, 78, 79]. The manipulator design aimed to offer maximizing the load capacity with a swift manipulation capability. It should be clear that the grippers and manipulators are two different types of systems; even if the manipulators described here are able to lift an object, "grasping" is considered a different task, performed not by a continuum arm, but by a gripper.

Further picking from nature, adhesion based gripper employing microfibers has also been realized. The gripper was developed using a 3D printed syringe pump to apply pressure on a soft inflatable membrane to change the stretch configuration for gripping and un-gripping [80].

Constituent materials, generally describing, employed for these soft gripping systems are made-up of a combination of elastomeric materials, eliminating the rigid components from the systems. In recent years, SPAs are under major consideration, like in the development of the above mentioned soft grippers. The materials which have been employed for the development of various grippers highlight that these are constructed using two or more parts with different mechanical moduli in order to achieve required deformation or motion. Tendons, PAMs FEAs, EAPs are amongst the main actuation methodologies for such systems. The advantage of relying on soft materials for body construction of soft gripper, or generally the soft robots, is the variability of conceivable motions that such materials can offer with a simple structural mechanism.

Thus, the arrangement of different materials to construct an SPA - one prominent design is reported in [35] and a modular approach is reported in [46] - emerged as the accommodating solution for soft gripping systems. However, the fabrication and development turned out to be complex.

This chapter presents an effort aiming at the development of an SPA utilizing single material. We introduce SCM, with a single internal pneumatic actuation chamber to form an adaptable multiuse actuator with a simple construction. The module is cost effective both in terms of its developmental process and disposal of the impaired or damaged components.

As already briefed, the PASCAV gripper is an elementary design able to perform gripping action on flat, curved, and uneven surfaces or objects. The acronym PASCAV is a part of a series of soft robotic mechanisms being developed in various configurations for a range of different applications, utilizing the same fundamental SCM.

4.2 PASCAV Gripper

4.2.1 Application of SCM as PASCAV Gripper

The construction of the SCM facilitates to apply SCM in a diverse range of solicitations. The actuation chamber of the SCM has the ability to apply force as well as to act as a suction chamber owing to the softness and flexibility of the material. For the current application, single SCM block has been employed to realize PASCAV gripper. Developed gripper with its normal and an actuated state has been illustrated in Fig. 4.1. It represents the gripper in its final shape: (a) is the normal or rest state of the gripper; while upon pneumatic suction, (b) represents the actuated state of the gripper. The suction pressure was generated utilizing a manual suction pump.

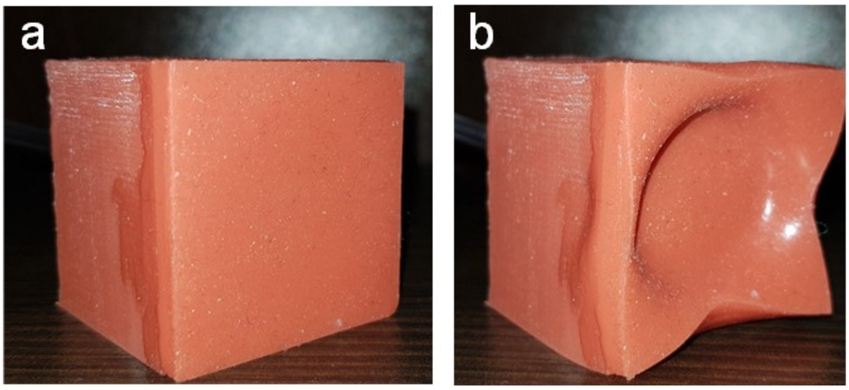

FIGURE 4.1: (a) PASCAV Gripper at rest state; (b) Actuated state.

4.2.2 Actuation Scheme

Upon pneumatic actuation, with suction effect the top covering layer of the pneumatic chamber adapts the shape of the cylindrical disk shaped cavity (Fig. 4.1). Depending on the shape of the target surface, plane or curved, corresponding vacuum is applied to achieve the respective contact between the gripper and the target surfaces. For plane surfaces, higher vacuum helps to adapt the plane shape and stick to that; while lower pressure helps to enwrap and adapt the uneven surfaces of curved or irregular objects to grasp them.

The edges of the cube adapt a curved contour that increases with increasing suction in the pneumatic chamber. This contour is helpful to grip the target surface; however, it starts to disrupt the grip depending upon the target surface shape and applied pressure. This disruption compels to opt for a suction pressure specific to the target object shape. Furthermore, we have observed that the performance of the gripper in terms of reliability of the grip depends on whether the internal top and bottom surfaces of the chamber come into contact or not when the SCM is actuated.

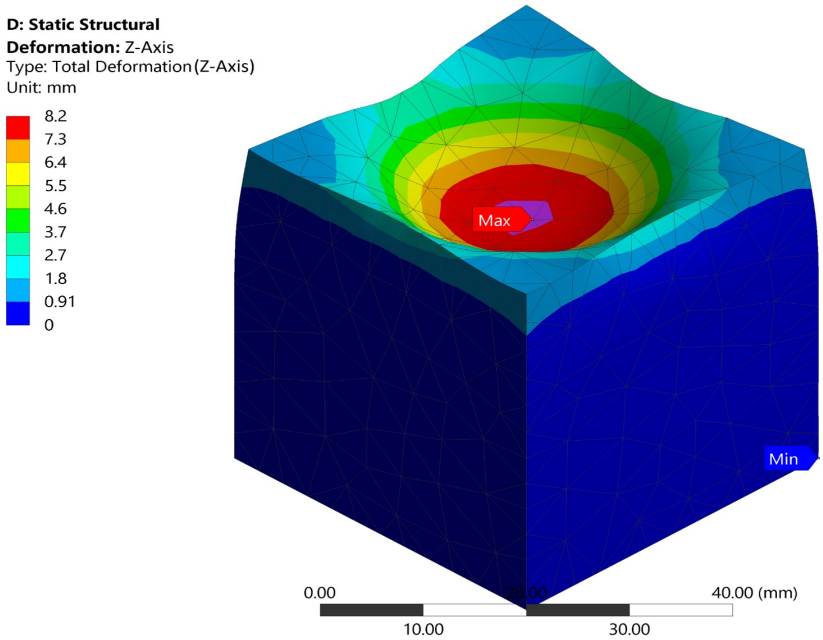

FIGURE 4.2: Directional deformation (dm) along ζ, coincident with Z axis in the system of reference of the simulation environment. The internal applied pressure is 1KPa.

4.2.3 Performance Analysis

Due to the opacity of the silicone rubber, assessment of the contact between the internal upper and bottom surfaces of the pneumatic chamber occurs just by visual inspection. For this reason, as well as for future design optimization of the SCM, we have implemented a finite element model.

F or the gripper actuation analysis in the current model, the SCM is discretized with 10-nodes tetrahedral elements and the bottom surface is fully constrained. To simulate the vacuum, an internal uniform pressure is applied, directed in such a way that the final effect is as shown in Fig. 4.2. The simulations have been performed taking into account the occurrence of large displacements; therefore, they consider not only material nonlinearities (due to the stress-strain relationship of the silicone rubber) but also geometrical nonlinearities. To simulate the contact between the two aforementioned surfaces, a contact condition has been set, with a penetration tolerance equal to a set of values from 0.1kPa to 10kPa.

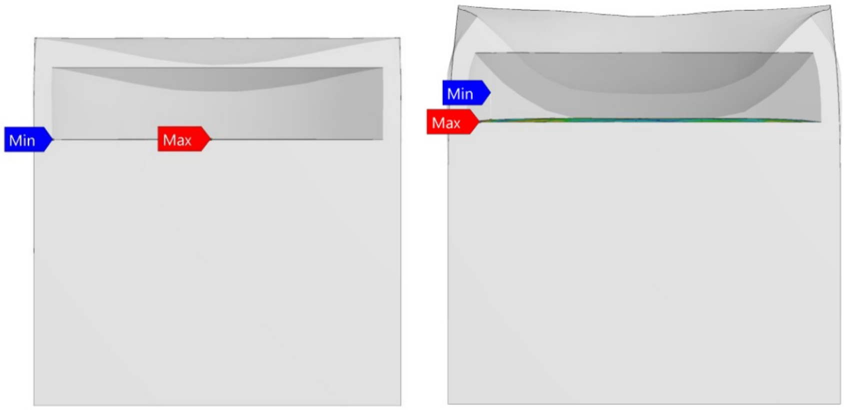

FIGURE 4.3: Area of contact between the internal surfaces of the pnuematic suction chamber: minimum (left) at 200Pa and maximum (right) at 1KPa.

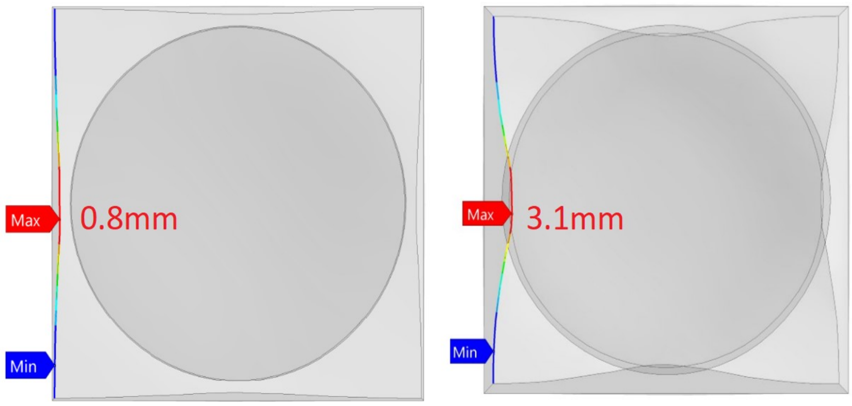

FIGURE 4.4: Distortion or deformation d_c at the edges of the cubical gripper: effective for minimum gripping (left) at 0.2Pa and for maximum gripping (right) at 1kPa.

The objective of the simulations is twofold: (i) to assess the relation between the area of the contact region against the applied pressure (Fig. 4.3), and (ii) to investigate the distortion of the four corner edges as a function of the pressure (Fig. 4.4). As explained in the following, the later might play a major role in the performance of the gripper, since an excessive distortion could jeopardize the ability of the gripper to work as suction envelop.

4.2.4 Surfaces Deformation and Gripping Effect

Upon actuation, the maximum deformation of the gripping cavity takes place at the center of the chamber along the principal axis ζ. This maximum displacement is denoted as d_m. The four edges of the cube along the activation chamber or gripping cavity, a curved deformation occurs whose contour depends upon the applied suction pressure. The maximum curved deformation (d_c) occurs inwards at the center of the edge orthogonal to ζ and to the face of the cube. There occurs another deformation in a small region at the center on all four sides of the cube where the thickness of the outer wall of the gripping cavity is the minimum. This deformation helps to accommodate d_c along the surface of the target object so that the gripping surface adapts the target shape developing an effective grasping of the object to pick it up.

The d_m becomes effective and is able to develop a grasping of plane surface target objects, when d_c starts occurring at 0.2kPa suction pressure. However, this initial stage remains valid for light weight object with plane surfaces. With increasing suction pressure, d_c increases, that enhances the range of gripping of the PASCAV from flat to curved or uneven surfaces. This second stage remains valid till the internal surfaces of vacuum cavity come into contact. Beyond that level, up to maximum d_c=3mm, the gripper remains applicable for flat surfaces and its grip for curved or unsmooth surfaces becomes vulnerable within this range.

Effective range of grasping of the gripper remains between 0.2kPa to 1kPa. Ideal state for curved surfaces gripping is d_m=7.8mm, along Z-axis or principal axis ζ. This ideal state occurs approximately at 0.5kPa suction pressure when the contact region of the internal top and bottom surfaces of the gripping chamber remains minimum, which allows the gripper's outer surface able to adapt and hold the target surface shape. At this stage the d_c remains

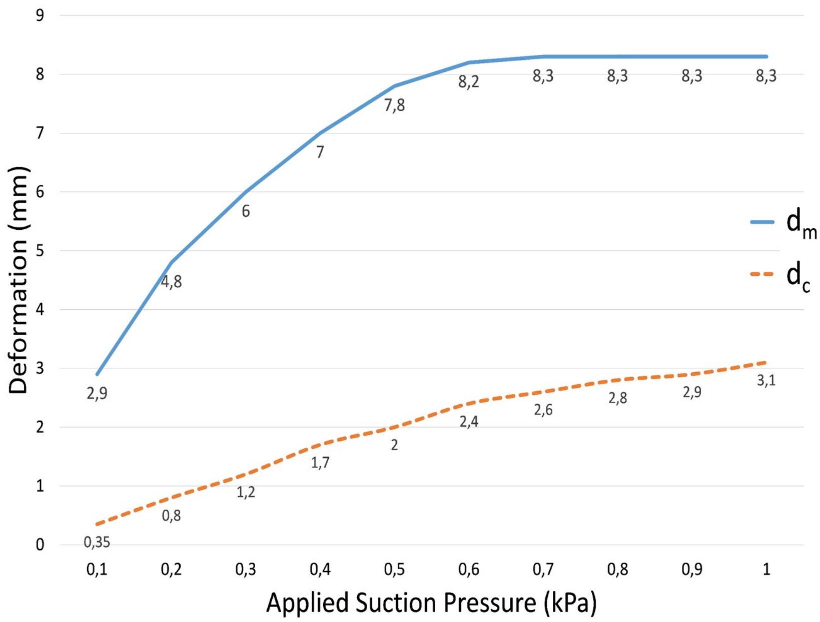

FIGURE 4.5: Maximum defromation (d_m) along principle axis ζ and maximum defrormation (d_c) orthogonal to the principal axis ζ.

around 2mm providing firm contact on the edges of the gripper. With increasing suction pressure, beyond 1 kPa, the deformation along the edges becomes $d_c$mm3. At this point, this increased d_c starts disrupting effective contact at the centers of the edges, especially to the plane or smoothly curved surfaces, making the grip vulnerable.

The deformation $d_m$along ζ increases rapidly from initial applied suction pressure to 0.5kPa from 0 to 7.8mm. Beyond 0.5kPa suction pressure the change in $d_m$is negligible, especially after achieving dm=8.3mm at 1kPa. However, the deformation d_c orthogonal to ζ increases gradually with the applied suction pressure. Fig. 4.5 represents the occurrence of $d_m$and d_c for the effective range of gripping of the PASCAV.

4.2.5 Experimental Results Analysis

The PASCAV has successfully carried out gripping actions on various types of objects including flat surfaces like cell phones with flat touch screen, unsmooth curved surfaces like fruits, smooth and premeditated curved surfaces like bottles and coins 4.6. Smoothly curved and flat surfaces have successfully been grasped within the effective range of pressure and deformations d_m and d_c. However, largely uneven surfaces are not applicable for this designed size of the PASCAV due to its cubical shape which can be fixed by increasing the actuation chamber height. For extensively uneven surfaces, the deformation d_c, on any of the four edges of the gripper with the current size, is likely to disrupt the grip at any stage of the actuation. The preferred solutions to eradicate gripping uncertainties are to opt for scalability with respect to the target surfaces, and to utilize multiunit gripping arrangement in order to retain the modularity and design schema of the SCM.

4.3 Overall PASCAV Gripper Evaluation

Although the PASCAV Gripper has shown a range of positive results, it has limitations in terms of target objects range that it can grasp. One such limitation is the height of the internal pneumatic actuation chamber or the grasping chamber which makes it difficult to grip and hold the object with steep curves like the curves on the longitudinal edges of an egg. For such kind of objects, the height of the suction chamber may need to be augmented. However, since we are working on scalable cubic designs, rather than changing the design scheme of the cube, utilizing different sized cubes for specific respective objects will be a potential remedy to this issue. This feature, the scalability of the cube, provides a wide range of applicability to this approach.

The next phase of the PSCAV design optimization is to evaluate the force profile of the gripper on its contact surfaces, especially at the edges to select the optimal the range of effective pressure, and the thickness of the four outer walls. An experimental setup with force sensors is being considered to evaluate the gripping forces. Another target is to realize a multi-block gripper in

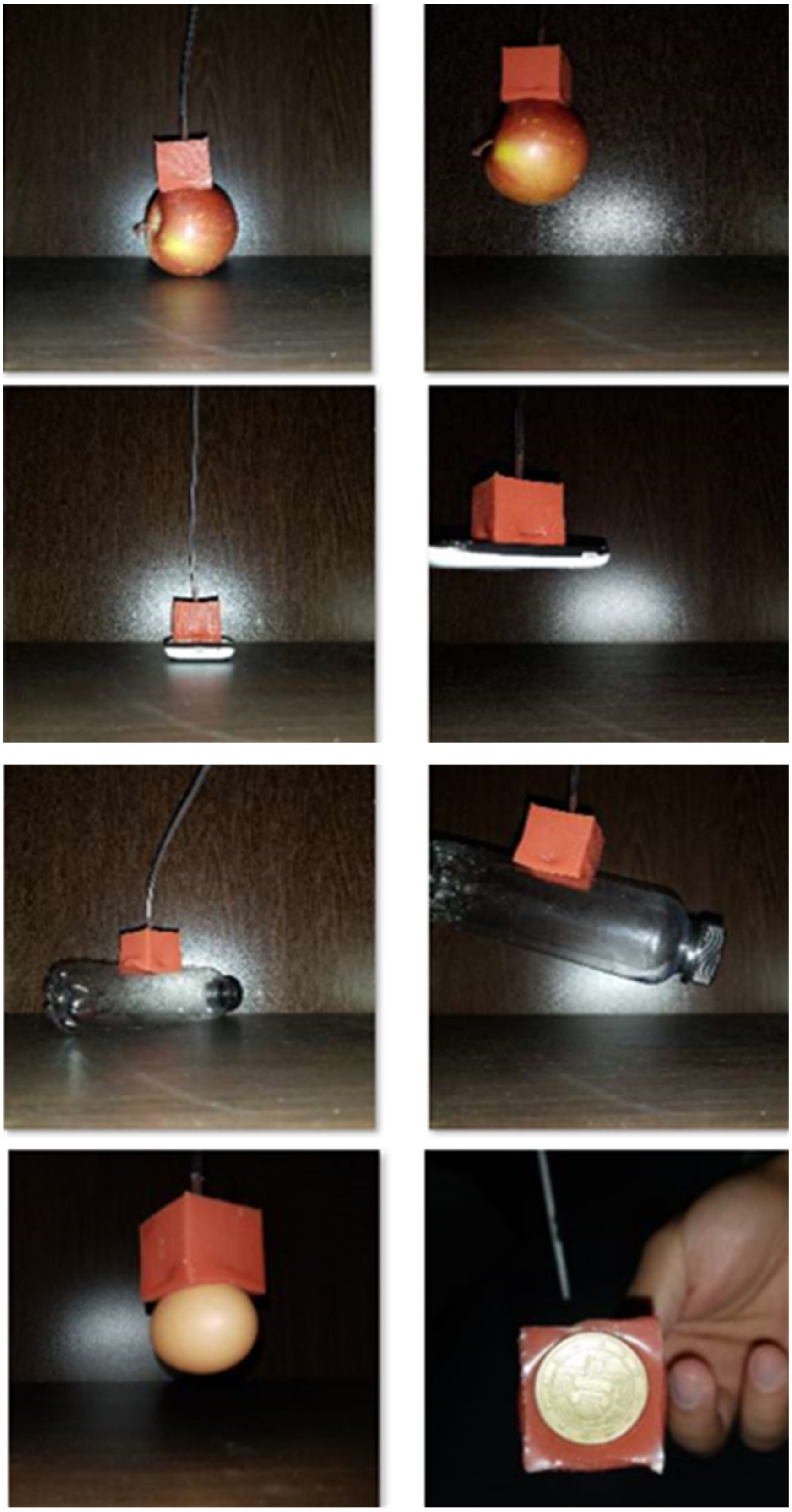

FIGURE 4.6: Applications: PASCAV Gripper effectively holding an apple, cell phone, bottle, an egg, and a coin.

order to increase the payload and to effectively grasp a wide range of uneven and unstructured objects.

Chapter 5

PASCAR: a Pneumatically Actuated Soft Cubic Archetypal Robot

5.1 PASCAR

The overall analysis and experimental results of SCM actuation performance encourage towards further exploration and implementation of multi-block combinations. Several SCMs can be assembled to build a soft robot. Since each SCM is a cube, two of them can be joined at any of their six faces. The connection can be created gluing the two modules with the same silicone rubber used to build them. We have verified that such connection provides sufficient mechanical resistance.

This chapter provides an example of soft robot made of only two SCMs. We consider it as an archetype of the soft robots that we can build using SCMs, that is, robots made of only one soft material and having a repetitive and easy to assemble structure. We name this robot PASCAR (Pneumatically Actuated Soft Cubic Archetype Robot). It is shown here that under a proper actuation sequence, PASCAR is able to move forward.

For instance, an elementary assembly of two SCMs has been realized which is able to perform locomotion on a flat surface. Two SCMs are joined together such that the top face of one SCM is connected to a side of the other SCM, making principle axes ζ_1 and ζ_2 of the two connected SCMs orthogonal to each other. PASCAR is actuated by applying pneumatic pressure in contrast to the vacuum based actuation in PASCAV. Sequences of actuating and neutralizing of pneumatic chambers in two SCMs make PASCAR to achieve displacement. The PASCAR design scheme is capable of accommodating variety of SCM orientations and their actuation patterns.

5.1.1 Orientation of SCMs in PASCAR Model

Fig. 5.1 shows in a schematic way the relative orientation of the two SCMs in PASCAR, from now on named SCM1 and SCM2.

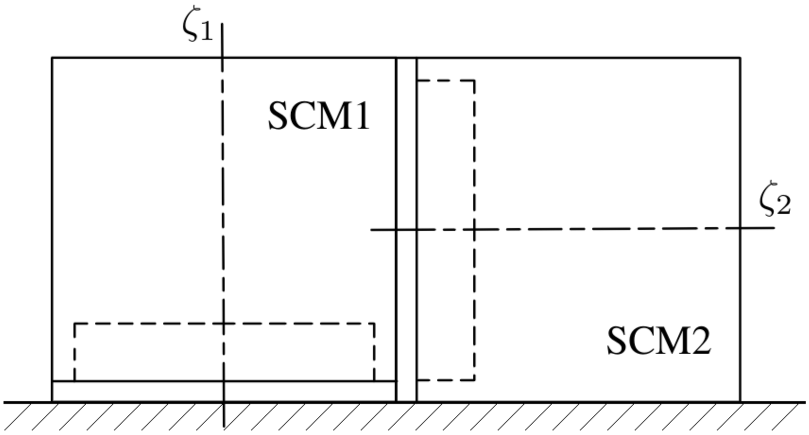

FIGURE 5.1: Schematic drawing of the SCMs in PASCAR. The channels for the pipelines are not represented

The internal chamber in SCM1 has its axis ζ_1 orthogonal to the ground. When actuated, SCM1 lifts PASCAR from the ground. SCM2 is oriented such that the axis ζ_2 is parallel to the ground and orthogonal to ζ_1. When SCM2 is actuated, its bottom face is displaced forward. SCM1 and SCM2 are connected as represented in Fig. 5.1: the top face of SCM2 is glued to one of the side faces of SCM1.

5.1.2 Actuation sequence

Since at this stage we have not implemented an automatic controller, the modules are actuated manually by using pneumatic pumps. Therefore, the results will be evaluated in terms of maximum rigid displacement achieved by PASCAR after one actuation sequence is performed. The applied actuation sequence is as follows. In the first place, SCM1 is actuated and lifts PASCAR from the ground (Fig. 5.2b). Then, maintaining SCM1 pressurized, SCM2 is actuated (Fig. 5.2c); if the friction force between SCM1 and the ground is sufficiently high, this results in a positive displacement of the SCM2 in the forward direction. Another effect of the pressurization of SCM2 comes from the deformation of its lateral faces: if the displacement d_s2 is such that the surface of SCM touches the ground, then a reaction force comes into being. This is crucial for PASCAR to proceed forward. In the next step, SCM1 is deactivated, returning to its undeformed configuration, but displaced from its original position (Fig. 5.2d). As final step of the sequence, SCM2 is deactivated (Fig. 5.2e). We have observed that this results is SCM2 pulling SCM1 in the towards the forward direction, but at the same time SCM2 retreats of a fraction of the displacement achieved before. The total rigid displacement of PASCAR after this actuation sequence varies between 1 and 2mm, that is, approximately 6 percent of L.

5.1.3 Stability

The design scheme is capable of accommodating variety of SCMs orientations and their actuation patterns: PASCAR is only one of the possible robots that we have assembled. For instance, we have tested another two SCMs system with both actuation chambers in the downward orientation touching the ground. Although this combination produces displacement, however, the

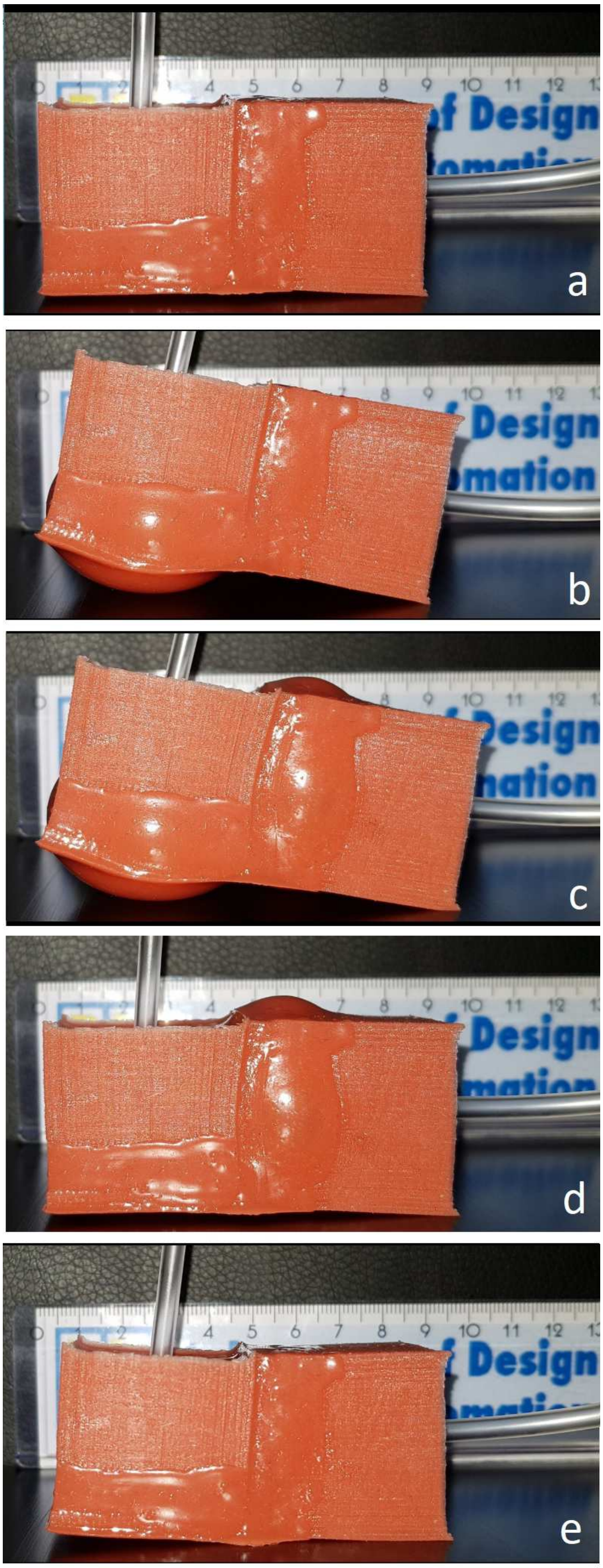

FIGURE 5.2: Actuation sequence to make PASCAR perform locomotion towards right direction: PASCAR is placed on the ground (a), MSC1 is actuated (b), MSC2 is actuated (c), MSC1 is deactivated (d), MSC2 is deactivated.

robot remains unstable as upon inflating both chambers, both ground surfaces become curved. On the contrary, PASCAR is able to move maintaining stability, since its front edge is far for the actuated chamber and therefore exhibits no deformation and remains in touch with the ground when SCM2 is actuated.

5.2 Finite element simulations

We have recurred to finite elements once again, to simulate the response of PASCAR to the actuation sequence described above. We have performed a static structural analysis, con- sisting of four steps, in which the actuation pressure in the two chambers are as shown in Fig. 5.3.

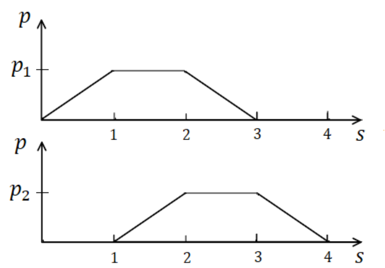

FIGURE 5.3: Actuation pressure set in finite element analysis: p and s are the pressure and the number of step respectively; subscripts 1 and 2 refer to SCM1 and SCM2

Despite the results of finite element analysis for the single SCM have been validated, since the deformed configuration computed was akin to the one of the physical SCM, we could not simulate correctly the response of the assembly of SCMs. We have observed that the problem does not lie in the computation of the deformed configuration of assembled SCMs; instead, the determination of the friction coefficient between PASCAR and the ground is not an easy task and it has a relevant influence on the results of the simulation. The computed deformed configuration of PASCAR at step 2 is coherent with what the reader can observe in Fig. 5.2c; however, assuming a value of

0.4 for the friction coefficient between PASCAR and the ground, its final rigid displace- ment is equal to 0.18mm. We have obtained unsatisfactory results by setting other values for the friction coefficient, and for several values of p1 and p2. Another aspect that it is worth remarking is that no dynamic effect related to the actuation rate is considered in our simulation, so far. This will be recalled in the next section.

5.3 Overall Performance of PASCAR

the current PASCAR moves of a short distance per one actuation sequence, compared to its total length. Its displacement varies depending upon the interacting surface material, like wood, plastic, hard floor, leather, paper etc. The best performance has been noted on wood and plastic surfaces. Although it has shown displacement on various surfaces, it is important to achieve a specific friction of PASCAR for a particular surface. We believe that this aspect can be improved performing size optimization of the SCM, to achieve optimal values of d_s and d_t (for instance, such that the maximum displacement when actuating SCM2 can be obtained). Design parameters would be the dimensions listed in Tab. 3.1, as well as the position of the axis of the chamber with the respect to the faces of the cube. Such kind of optimization can be performed by means of finite element commercial software, as done by other authors (for instance, in [81]). On the contrary, we have not developed yet a simulation setup to compute correctly the response of an assembly of SCMs, such as PASCAR. As anticipated in the previous section, it might be important to take into account frictional and dynamical (inertial) effects; this introduces further complication in a problem which is already nonlinear due to material properties and the occurring of large displacements.

Chapter 6

PASCAM: a Pneumatically Actuated Soft Chewing Articulation Mechanism

In this chapter, the main motivation and the consequent efforts are discussed. As already described in the 'Introduction', DIFERM was the driving idea to carry the development work on SCM. DIFERM has already been designed and developed, whereas, its alternative soft mechanism named as PASCAM is under consideration for further material selection and optimal design. Here, we will present a brief review on the state-of-the-art of the human mastication systems; the design of the DIFERM robotic mechanism; and the basic concept of the PASCAM design. PASCAM presents a novel formation of a manipulator that can potentially imitate the human chewing mechanism, and can act as an alternate to conventional approaches like Stewart robotic mechanism, with advantages of compactness, simpler kinematics design, easier control, fewer components, and economical in terms of overall system costs.

6.1 Dental Implants Force Evaluation Robotic Mechanism (DIFERM)

6.1.1 Robotics in Medical Field

Medical field is one of six major application areas of service robotics [82]. Robotics application for health care is growing since 1980's for better patient care [83, 84]. This opening out can be witnessed from research output in medical robotics during the last decade as compared to the other applied areas [85]. Among the service robots, medical robotics holds the second highest value, which tends to increase by four times within next three years [86]. Despite the availability and accessibility of hi-tech tools and upsurge of robotics in medical processes, the application is still limited due to the cost of applicability, safety requirements, as well as the complexity of robotic systems [87, 88, 89]. The presence of robotics technology in dental care is further scarcer. The current work is a particular effort to assist a specific issue in prosthodontics. It presents a robotic machine for the dental implants laboratory services that employs a robotic device articulated for the identification and recording of loading effects of dental prostheses on the jawbone.

6.1.2 The Need for Robotic Chewing Mechanism

For the successful implantation of a dental prosthesis, its placement and orientation into the jawbone is critical together with design and material [90, 91]. Decayed or damaged states of the jawbone necessitate jawbone evaluation. Health and strength of the jawbone plays important role in the life and stability of an implant [92, 93, 94]. For the jawbone quality and stiffness evaluation, x-rays and Computed Tomography (CT) scan are in practice [95]. These evaluations along with preceding statistical data analysis of implants success rate in various regions of the jawbone, help to orient and place an implant. Experience and skills of the dentists are crucial in this regard. However, the evaluation of implnat-jawbone interactive loading has not yet been facilitated effectively. For the purpose, robotics technology has been considered in the current work.

6.1.3 Robotic Masticatory Systems: a Brief Review

Generally, robotic mastication systems have been developed for rehabilitation, food sciences, and dental implants design and material testing [96]. The main focus remained to reproduce the bio-mechanics of human mastication.

A human mastication system was realized for rehabilitation purposes of temporomandibular joint disorders and 'open bite' malocclusion. It was initially designed with a single Dof antagonistic muscle model, which was later modified to a three Dof masticatory robot [97, 98, 99]. The manipulator was further reconfigured into a 6-Dof parallel mechanism for maximum dexterity [100, 101]. The main emphasis of these designs was to replicate the human masticatory performance in terms of mechanical structure, Dof and sensing capability. A modified version of the same manipulator was further utilized to evaluate the chewing effects on the food stuff for texture analysis [101]. Some other masticatory robotic designs, based on bio-mechanics and human mastication anatomy, employed in food sciences include a 6 Dof parallel kinematic manipulators, a 6-bar linkage robotic system, and a tendon-spring mechanism to design a life-sized mastication robot [102, 103, 104, 105, 106].

Material and strength validation of the dental implants got robotic assistance. The biomimetic chewing robot is also considered suitable for dental material testing based on its redundant kinematic structure [104]. In another effort to produce occlusal forces for the evaluation of various designs of dental implants, a commercial SCARA robots was used for positioning accuracy and control to execute masticatory movements [107]. For dental implants restorative materials testing, a Stewart manipulator was used to evaluate their strength against simulated chewing forces [108, 109, 110, 111]. For dental implants fatigue testing and their structural safety analysis, industrial grade systems have also been developed. These are mainly uni-axial compression and tensile testing equipment to conduct monotonic and cyclic tests [112, 113, 114, 115]. These testing systems are employed for standardization against ISO 14801, and for dental implants material wear [116, 117, 118].

These reported efforts are the robotic systems capable of generating human mastication and jawbone movements mainly employing parallel kinematic mechanisms (PKM). Kinematic design of such systems was inadequate to implement a parallel mechanism effectively in order to further examine the effect of produced resultant interactive forces between implants and the jawbone. The focus was generally on mandibular bio-mechanics and consequent use of manipulators or the mechanisms moving an end-effector plate. Although the motion capability of the developed systems ranges from single to kinematically redundant, however, force sensing remained limited to fewer axes, resulting in inadequate feedback about forces and moments. The control loop of these developed actuators is based on position and velocity feedback, and are deficient in force feedback in control loop which hinders to achieve the required level of chewing force cycle replication. Eventually, this results in inadequate interactive load examination.

6.2 Stewart Platform Based Robotic Chewing Simulator

The principal approach for the present machine development is to realize a medical laboratory testing equipment keeping the design substantially smart with industrial grade reliability. This approach leads to the design level standardization of system components and to achieve the optimum level of the life-cycle and the functional performance of the equipment. It further assists in bridging the gap between academic research and industrial grade design leading towards the commercialization of the developed system as an innovative addition to the dental studios and laboratories. A good level of consideration was devoted to the optimization of stable machine layout in order to replicate the complex action of the mandible on the upper dental arch focusing on chewing cycle forces to be executed.

A Robotic system is designed replicating chewing forces of human jawbone. The system needs to be capable of generating chewing cycles manifesting relevant forces and moments which are exhibited by the lower jawbone, mandible, on the interfacing upper jaw, maxilla. In the current mechanism, end-effector of the robotic device or the PKM acts as the mandible that interacts with the fixed dental implants module being examined. The dental implant module is an especially designed force sensing component providing interfacial forces between each implant-screw and the respective host jawbone. The developed PKM has a well known structure of Stewart mechanism. The current mechanism has six linear hydraulic actuators, connected between two plates, base and the end-effector, through floating joints. The kinematic chain of the mechanism has spherical-prismatic-spherical (SPS) configuration for each leg. The end-effector is extended through hydraulic legs actuation. Floating joints compensate backlashes while acting as the spherical joints in the mechanism. A six-axis load-cell, the force-torque sensor, is attached at the top of the end-effector which interacts with the dental module to be examined during the operating cycle.

The PKM has 6-6 type configuration with respect to its legs assembly between the base and the end-effector (Fig. 6.1).

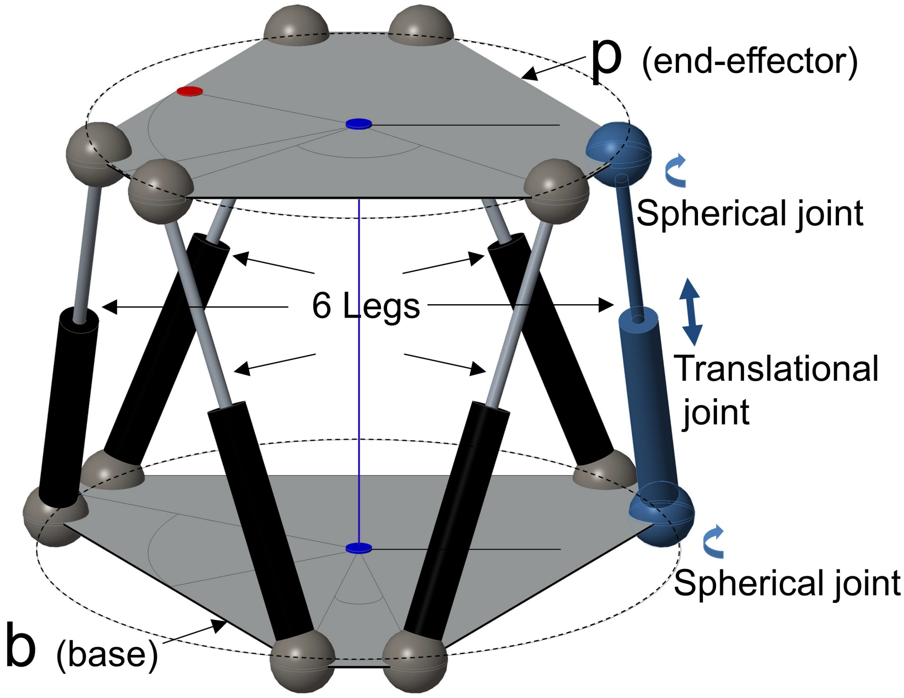

FIGURE 6.1: Geometrical representation of Base and End-effector plates, and vertices distribution.

6.2.1 Hydraulic Actuation System

The chewing wrenches have been realized employing an unconventional hydraulic actuation scheme. This actuation scheme of the PKM has two stages: the initial extension of the end-effector to get engaged with the test module; and the second stage where the end-effector exerts multi-axis forces on the test specimen. The first stage is simple in terms of extension of all legs to reach and get in contact with the target surface. This stage needs hydraulic flow for the extension of the hydraulic actuators simultaneously. The second phase of the operation cycle involves force application by the end-effector on a fully constrained surface. This stage involves critical hydraulic flow control to achieve the required hydraulic pressure corresponding to the respective force requirement in a particular actuator. The actuation scheme realized to accomplish the both operation cycles of the PKM has been described further.

The hydraulic circuit comprises six double acting hydraulic cylinders which are the six legs of the PKM, linked to a constant flow rate hydraulic source from bore sides and to a gas-charged hydraulic accumulator from their rod sides. Hydraulic accumulator keeps the end-effector at its default fully retracted position at the initial point. During the first stage, the flow source needs to supply the flow, overcoming the accumulator pressure, in order to extend the end-effector towards the target surface. Once both surfaces are engaged, The hydraulic source maintains the required fluid supply against any pressure differential to ensure necessary forces at the end-effector. For this phase of the operation, to control the hydraulic flow and pressure, each hydraulic cylinder employs a needle valve and a pressure relief valve. The needle valves control the hydraulics flow to the respective actuator while the pressure relief valves maintain the required pressure in the respective line by bleeding the excess fluid volume. Hydraulic architecture for a single leg has been depicted in Fig. 6.2. Hydraulic source is a constant displacement pump with constant speed, so the volumetric flow remains constant. There are some volumetric losses that depend on the system pressure dynamics. Needle valves which are manually operated have been set to fixed open state. An ideal controlled pressure relief valve whose losses are calculated nearly to real case has been utilized for each actuator. Accumulator with a pressure of 100bar pre-charged is engaged.

The end-effector is equiped with a load-cell which makes contact with the implant module throug a load plate. This load-cell provides 6 axis wrench at the interface. Six hydraulic cylinders of the PKM are equipped with respective pressure sensors which read the real time pressure of each cylinder at any specific position during the operational cycle. Wrench from the 6-axis load-cel and pressures reading from hydraulic cylinders must satisfy the relation

$$MF = W$$

where:

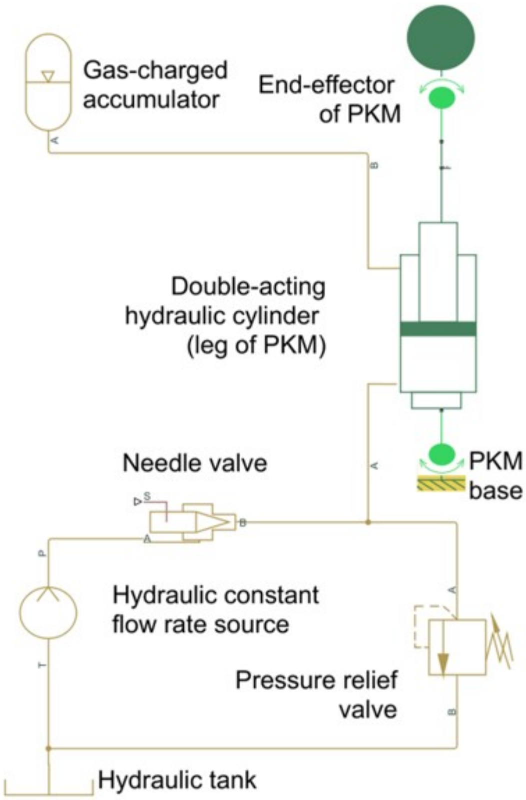

FIGURE 6.2: Hydraulic actuation system for the PKM.

M = Parametric configuration

F = The force vector at end-effector

W = The wrench (combined effect of forces and moments) at the end-effector

in such a way that the system is solved with regards to the leg extensions in order to obntain the parametized configuration. Furthermore, the control of the hydraulic cylinders is done using this parametric configuration to distribute an error on the total wrench in errors on the 6 cylinders or the legs of the PKM. This lookout configuration profiling for the motion control further facilitates to avoid additional sensitization of the leg extension. The position sensing of the legs have not been incorporated to keep the systems complexity and cost at lower level along with the system design which is not necessarily to be a manipulator for peculiar pose identification.

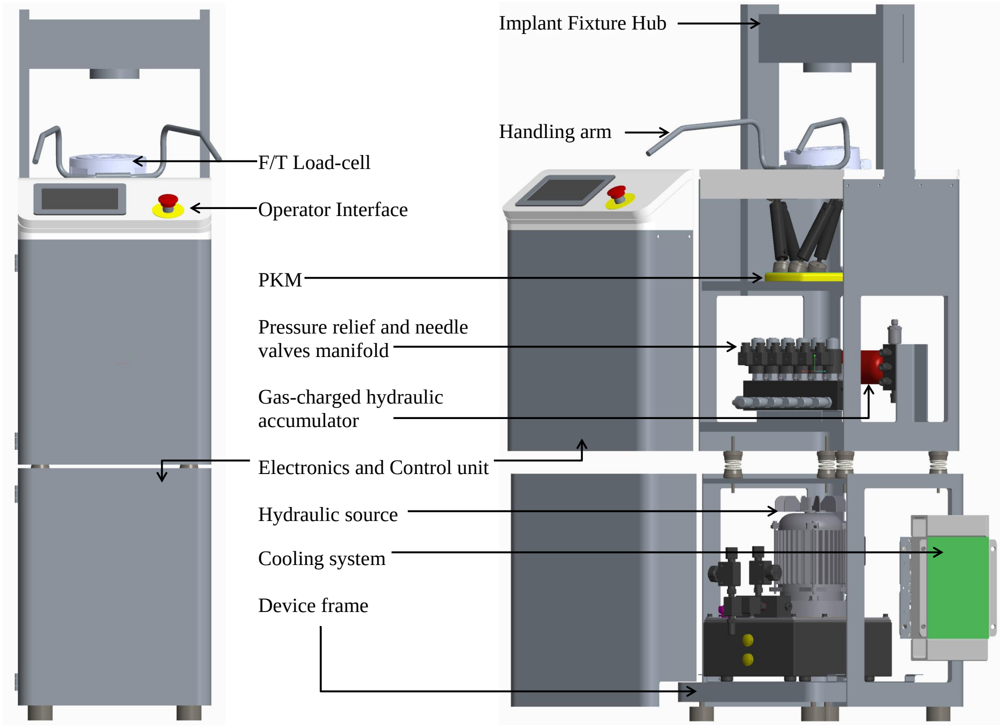

FIGURE 6.3: The design of the DIFERM chewing simulator machine.

The parametric configuration is further enhanced and validated by developing a system level calibration profile employing additional pressure sensors at hydraulic source and the gas-charged accumulator.

6.2.2 DIFERM Prototype Design

The overall machine architecture has been conceived based on modular approach (Fig. 6.3). Four major modules of this robotic chewing apparatus include: the PKM equipped with force-torque load cell; the hydraulics module for the actuation of the PKM; the electronics, control and operators interface module; and the dental specimen fixture module. The PKM, its hydraulics architecture and the design of the load recording sensor has already been discussed in the earlier sections. Interface and the electronics module which facilitate to operate the chewing simulator, extraneous to the prime description of the current paper, has been considered to present separately.

The focus of this machine development is multifaceted. It represents a cost effective dental laboratory equipment, having an innovative system design, which offers an unconventional methodology to implement the robotic PKM in order to examine the implant-jawbone loading interaction. The components of the PKM including hydraulic actuators, floating joints and the both base and the end-effector plates are customized for this specific design model. Floating joint has been employed as self alignment couplers for the hydraulic legs. The joints shape has been designed to accommodate the required skewed orientation of the legs between the PKM base and the end-effector. The skewed shape of the joint has been opted for convenient machining of the base and end-effector plates. Similarly the valves employed in the hydraulic circuit have also been customized as per the system requirement. The customization of these components has been done to achieve the compactness of the system and to achieve an overall cost effective solution.

Particularly with respect to the novelty of the chewing simulation design, in contrast to the focus of many other efforts where mandible motion is accomplished by means of manipulators moving an end-effector plate with a focus on displacement, the current device focuses on force transmission between interacting bodies with minimal motion manipulation. This novel approach make this device to execute chewing force cycle with proper replication of real chewing, which facilitates the better recording of testing data.

6.3 The PASCAM

SCM is again the fundamental block of this mechanism as well like PASCAV and PASCAR. A modular approach has been followed to design PASCAM: the first module is the SCMs holding unit; the second module is the actuation unit which holds the mandible jawbone model and is manipulated by the SCMs to simulate the chewing alike motion profile; and the third module is the set of SCMs being employed as the actuator. The current PASCAM model has 4 Dof (Fig. 6.4) employing six SCMs. The two translational motions, lateral and vertical, in horizontal and frontal planes are compensated within rotational movements in respective planes. The jawbone movements are interdependent of rotational and translational motions during a chewing or mastication cycle owing to the special morphology of the temporomandibular joint [119]. Furthermore, this arrangement helps to keep the construction of archetypal soft chewing mechanism simple. PASCAM facilitates three rotational motions which are pitch, yaw and roll, and the heave translational motion (Fig. 6.4).

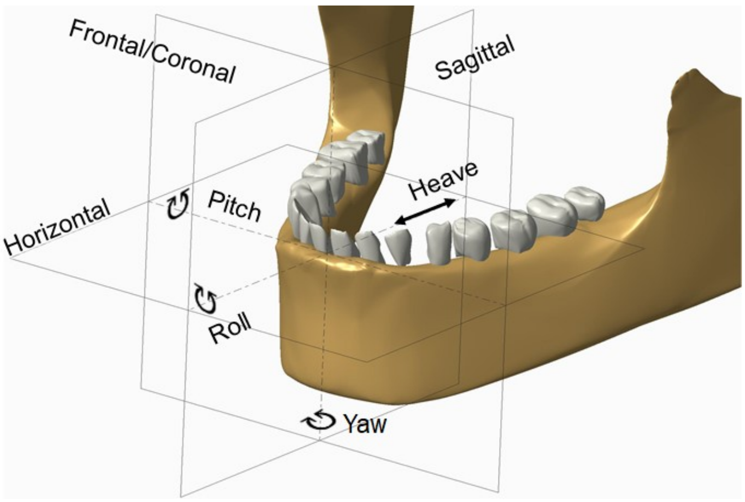

FIGURE 6.4: Jawbone movement planes and the PASCAM 4 Dof motions: pitch, yaw, roll and heave.

6.3.1 PASCAM Design Considerations

For designing of PASCAM manipulator, following measures have been considered:

1. Degrees of freedom
    - Pitch, yaw and roll rotational Dof.
    - Heave translational Dof.

2. Displacement ranges

   - Maximum motion is required along the pitch which is 40-50mm [120].
   - yaw rotation and heave are considered as 10-12mm and 8-11mm respectively.
   - and roll equals to approximately 1mm.

This design is addressing the archetypal realization of the chewing simulator in order to articulate the jaw movements and its basic dynamic.

6.3.2 PASCAM System Modules

PASCAM conceptual design has been presented in Fig 6.5.

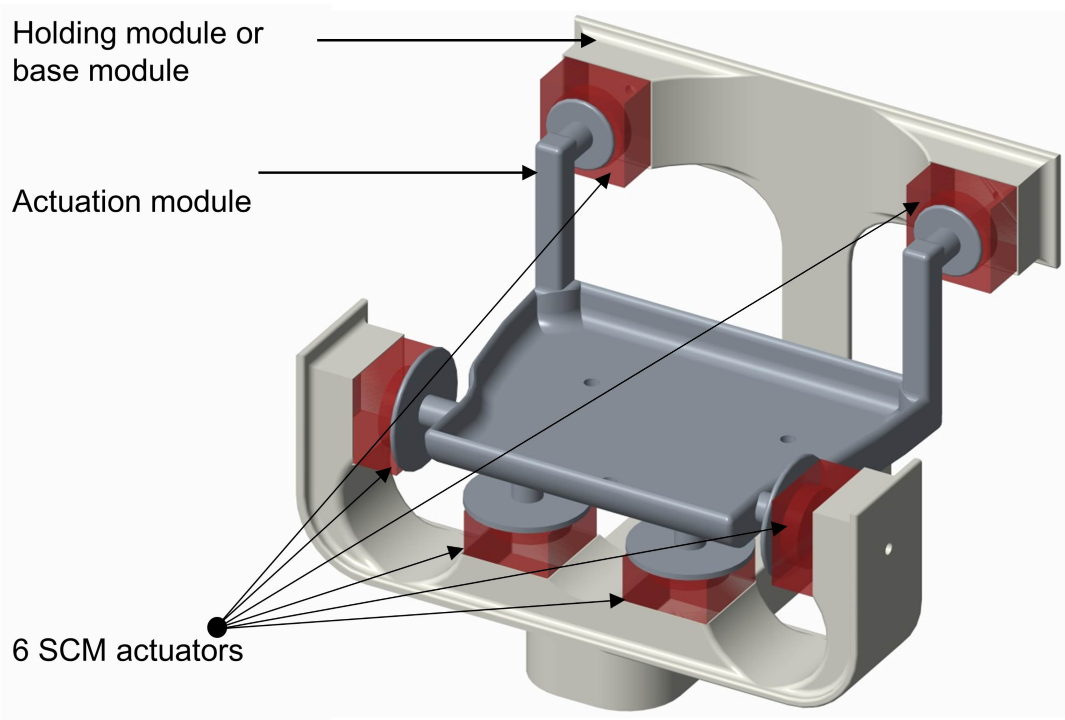

FIGURE 6.5: PASCAM design representing its 3 main modules.

1. SCM Holding Module: This module holds the six SCM units. Holders for three couples of SCMs A B, C D, and E F are orthogonal to each

other with respect to the principal axes *zeta* of SCMs. It accommodated the SCMs and thier pneumatic lines.

2. Actuation Module: This is the module which is manipulated by the SCM unites. It is manipulated to execute the chewing or mastication movements. Its design has been considered so that it can host a jawbone model in such a way that the PASCAM can be used to replace Stewart mechanism in the DIFERM.

3. SCMs in PASCAM: The prospective manipulator to satisfy these conditions is composed of a hierarchical modular design employing three modules as described earlier. It utilizes six SCM units arranged in an innovative manner which facilitate the holding and manipulation of the actuation unit. SCM units, A, B, C, D, E, and F, employed in this mechanism are providing the following functions:

   - SCMs A and B are working as the holder of the actuation unit. This configuration serve as the temporomandibular joints arrangement. A and B, working as PASCAV, holds the actuation unit as well as provide heave translation within the allowable range keeping the effective grip of the actuation unit.
   - C and D provides two Dof motions: pitch and the yaw.
   - E and F serves to provide roll and, owing to their positioning, additionally facilitate to keep the actuation unit aligned within the mechanism.

All SCM units being considered for archetypal configuration of PASCAM are identical (Fig. 6.6).

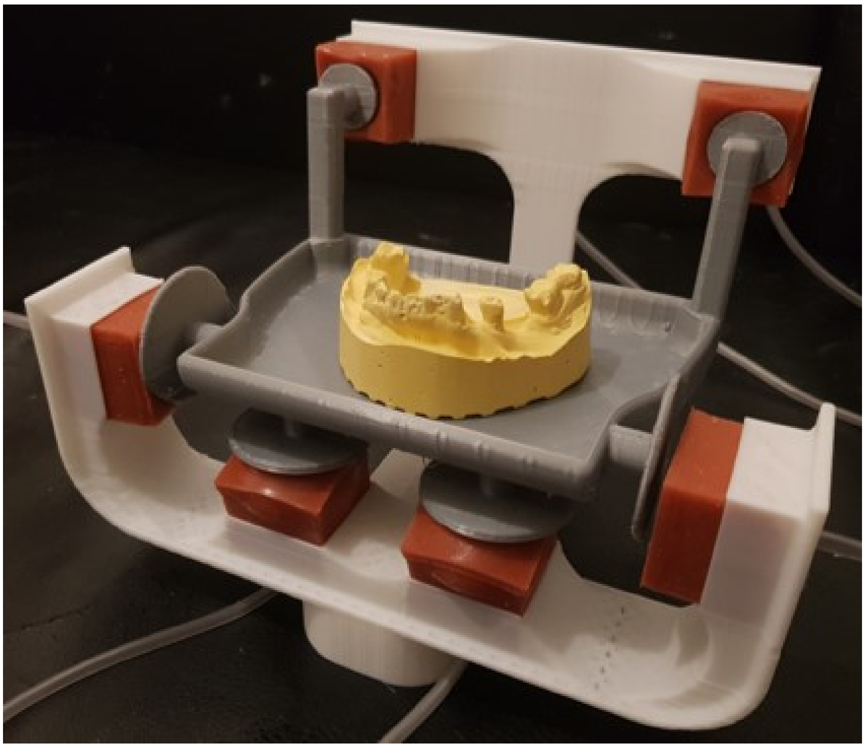

FIGURE 6.6: PASCAM archetypal 3D prototype for initial design validation. SCMs A and B are in fully actuated state gripping the actuation unit while C and D are generating pitch.

6.3.3 Key Design Considerations and Constraints

The key design constraints or points to take care that has been highlighted by the initial analysis phase are listed below:

1. Material selection. In the current case, silicone shore 'A' strength has been implemented. Material consideration is important as it affects the force transmission to the target object. Very soft or hard material will hinder force transmission by hindering the displacement or absorbing the applied pressure.

2. Finalization of optimal Dof requirements for the PASCAM to mimic human jawbone motions with respect to different translational and rotational motion ranges in different planes.

3. SCM units arrangement, number and sizing needs to be figured out optimally.

4. Actuation scheme and control configuration will also be a critical matter for the manipulator in order to achieve required forces in carrying out a chewing cycle.

Chapter 7

Conclusion and Future Directions

This study presents the evaluation of the geometrical configuration of SCM to realize a pneumatically actuated soft robotic actuator. The purpose of this scheme was to design the actuator with qualities of modularity and scalability in order to further develop soft robotic mechanisms.

The design scheme of SCM is helpful in realizing a simple and cost-effective SPA which is modular and scalable, and it employs a single soft material. The proposed design is a pneumatically operated system comprising commercial silicone rubber material based modular hyper-elastic actuator, SCM. It has one internal fluidic chamber which is actuated pneumatically to generate effective single axis deformation. The produced deformation is adequate and suitable enough to be utilized for actuation by exerting forces on the interacting surfaces under the applied pneumatic pressure. The actuation chamber's shape, size and orientation have been evaluated to realize an applied design which has been further employed for the development of modular soft robotic systems. Soft Cubic Module can be easily manufactured through molding process. Its external cubic shape ensures the stability of the module and facilitates its utilization as a single block actuator as well as makes it easy to combine multiple SCM units to build multi-unit robotic systems. This design scheme has been considered as the first tool to investigate its performance to execute certain given tasks in various configurations. SCM block has wide application range from a simple push button to the formation of a bio-mimicking robot and multi-Dof mechanisms. Archetypal arrangements of the SCM have suggested a wide range of possible mechanisms which are under further consideration for design analysis and development.

With respect to application specific considerations presented here, the PASCAV Gripper has shown a range of positive results, however, it has limitations in terms of target objects that it is able to grasp. One such limitation is the height of the internal pneumatic actuation chamber or the grasping chamber which makes it difficult to grip and hold the object with steep curves like the curves on the longitudinal edges of an egg. For such kind of objects, the height of the suction chamber needs to be augmented. However, since we are working on scalable cubic designs, rather than changing the design scheme of the cube, utilizing different sized cubes for specific respective objects will be a potential remedy to this issue. It also imples that the scalability of the cube provides a wide range of applicability. The next phase of the PSCAV design optimization is to evaluate the force profile of the gripper on its contact surfaces, especially at the edges to select the optimal the range of effective pressure, and the thickness of the four outer walls. An experimental setup with force sensors is being considered to evaluate the gripping forces. Another target is to realize a multi-block gripper in order to increase the payload and to effectively grasp a wide range of uneven and unstructured objects.

Similarly, speaking about the performance of the PASCAR, it moves of a short distance per one actuation sequence, compared to its total length. Its displacement varies depending upon the interacting surface material, like wood, plastic, hard floor, leather, paper etc. The best performance has been noted on wood and plastic surfaces. Furthermore, it has shown displacement on various surfaces, however, it is important to achieve a specific friction of PASCAR for a particular surface. This aspect needs further size optimization of the SCM, to achieve optimal values of d_s and d_t. For instance, the maximum displacement in equivalence to the deformation d_t is deemed obtainable while actuating SCM2 of the PASCAR. Such kind of optimization can be performed by means of finite element commercial software. As anticipated, it might be important to take into account frictional and dynamical (inertial) effects; that introduces further complication in a problem which is already nonlinear due to material properties and the occurring of large displacements.

The PASCAM design presents a novel formation of a manipulator which is able to simulate chewing alike movements. This design has shown the capacity as an alternate to the conventional Stewart platform, with advantages of compactness, simpler kinematics design, easier control, fewer system components, and lesser cost. The main application in view is a device to be used for jawbone force cycle evaluation for the bone strength examination. The analysis of the design of the robotic manipulator depicts successful validation of motion generation with specific actuation chamber shapes and corresponding execution. The future work is to optimize overall design of the robotic manipulator including material optimization, firing pattern of actuation chambers and maximum force transmissibility. Particularly with respect to the novelty of the chewing simulation design, in contrast to the focus of many other efforts where mandible motion is accomplished by means of manipulators moving an end-effector plate with a focus on displacement, the current design focuses on force transmission between interacting bodies with minimal motion manipulation. This approach will make this device to execute chewing force cycle with proper replication of real chewing, which will facilitate the better recording of testing data.

The overall analysis and experimental results suggest implementation of SCM to realize soft robotic mechanisms. It is anticipated that further studies on SCM will allow finding the optimum value of the ratio ‘r’, which is the ration of deformations on actuated surfaces of the SCM, for any specific soft robot built using SCMs. While performing size (and eventually shape) designing of the internal chamber, the cubic of shape of the module will be maintained, for the reason to make the assembly of multiple units convenient. The cylindrical chamber profile is under further evaluation for modification to achieve improved results. The current design has been evaluated to exhibit the capacity of the SCM to deform under applied pressure, however, it is under consideration to optimize the design for application of forces as required in PASCAM configuration to generate forces equivalent to the chewing forces. The modified profile would potentially be transformed into a convex disk shape which generates more forces at the actuated surface of the SCM cube than the cylindrical actuation chamber. Furthermore, the elliptical and curved horn shaped actuation chambers are also under consideration to achieve two axis deformations like the torsional deformation.

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